Development and Verification for the Control Method Using Surplus Pressure of Primary Pumps in Chiller Plant Systems for Air Conditioning which Adopts Primary/Secondary Piping Systems

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Abstract:
The primary/secondary piping systems are often employed in large chiller plant Systems. Normally, the primary flow becomes more than secondary flow, and the flow difference returns to a chiller via decoupler, which is common to primary flow loop (chiller side) and secondary flow loop (load side). It is a huge energy loss, because the primary pumps use their head to lead much flow to the decoupler. Therefore, we have developed new control method using surplus pressure of the primary pump to reduce the primary and secondary pumps' energy. In this paper, we used this control method to the actual chiller plant buildings and verified its effectiveness. As a result, cold water conveyances, both primary loop and secondary loop, could be covered by only primary pumps during plant operating time, and the water conveyance power energy was reduced approximately 80%.

Keywords:
Primary/Secondary piping system, Water conveyance power, Control method for energy conservation

Introduction:

The primary/secondary piping systems shown in Figure-1 are often employed in large chiller plant Systems which have more than two chillers. Primary/secondary systems have two flow loops, the primary loop with chillers and the secondary loop with the loads, and each loop has primary pumps and secondary pumps for the cold water conveyance. The pipe, "Decoupler", is common to these two flow loops and is connected between chillers and loads. The load, for example, air handling units in the secondary loop, has a two-way control valve, and so the secondary flow is changing by the load. On the other hand, the primary flow through the chillers is normally constant for maintaining chiller stability. The decoupler allows the pumps to operate at different flow rate. Normally, the primary flow becomes more than secondary flow, and the flow difference returns to a chiller via decoupler. It is a huge energy loss, if the big difference continues between primary flow and secondary flow, because the primary pumps use their heads to lead much flow to the decoupler. Therefore, we developed the control method using surplus pressure of the primary pump to reduce the primary and secondary pumps' energy. This control method ensures the smallest flow to maintain the chiller operation and saves the water conveyance power by utilizing the surplus pressure of the primary pump to the secondary, though the flow has returned to a chiller via decoupler until now. The days which are required for a full capacity must be few in the buildings for business use, so the actual loads are in a low condition for the chiller capacity in most of a year. The load is a partial load for the operating chiller capability when the secondary flow becomes lower than primary flow, so the occurring frequency is very high. In this paper, we explain the “Control Method Using Surplus Pressure of Primary Pumps” and describe the substantiated effects of energy reduction in the actual plant systems.

1. Summary and Problems of Conventional Cool water conveyance Control Method

The general control as a secondary conveyance control of cool water in primary/secondary piping systems is a secondary pump inverter control to keep the secondary supply water header shown as "SH-2" in Fig.1, and the operating pump number control depending on the load flow rate. It is general that the set-point of secondary supply header pressure for the inverter control is set to the total head of its rated flow by the secondary pump. For example, in case of the rated operating point of secondary pump, 5m^3/min(flow rate) and 300kPa (total head), shown in Fig.2, 300kPa (about 30m-aqua) total heads are the target value for the inverter control. If the load flow is 1m^3/min and is controlled to 300kPa target value, the frequency decreases to only approximately 48Hz because of the pump operating frequency characteristic figure shown in Fig.3. In this case, the 300kPa total head is not required, and the pump system applies excessive pressure to the secondary cool water loop. In fact, energy saving effects are not enough because the set-point becomes high condition in most time of a year by operating the designed value of maximum load flow, though the secondary pump is controlled by an inverter.

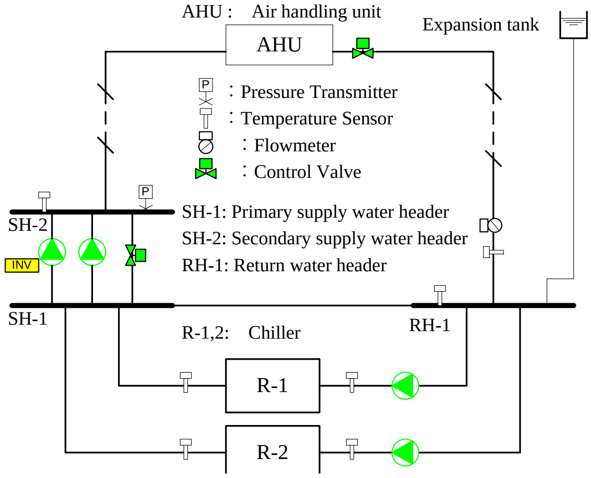

Fig.1 General Primary/Secondary Piping System

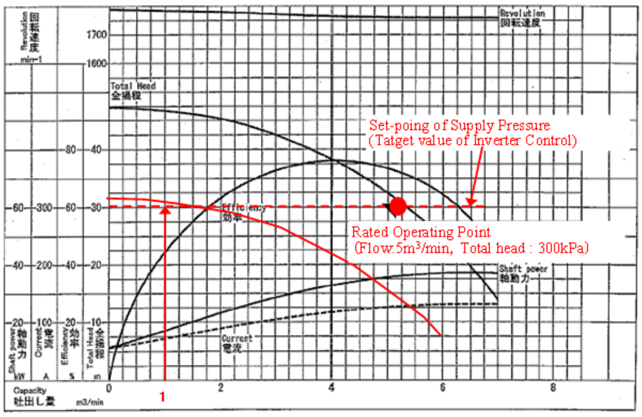

Fig. 2 Performance Curve of a Secondary Pump

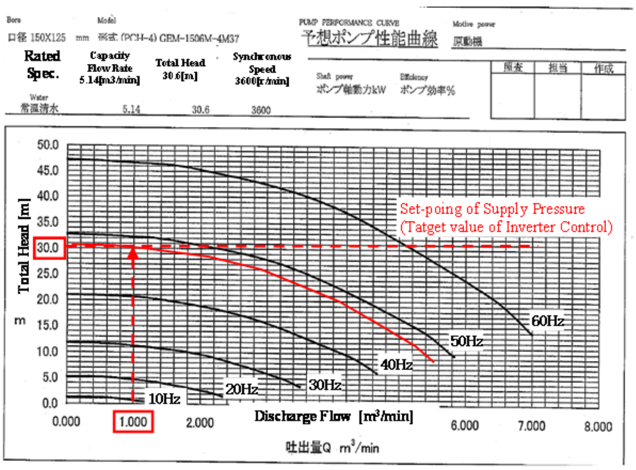

Fig.3 Frequency Characteristic of Secondary Pump

2. The Control Method Using Surplus Pressure of Primary Pumps in Chiller Plant Systems

2.1 Control Method Outline

The control method that we developed enables practical use of primary pump surplus pressure at the secondary cool water conveyance loop in order to reduce energy consumption of conveyance electric power. Instrumentation devices required for this control are only three devices shown in Fig.4, a pressure transmitter for measuring secondary supply header (Ps2) and primary supply header

(Ps1), a pressure transmitter for measuring the end pressure at the end point of the chiller plant (Pe), and a two-way control valve installed to the decoupler (V2, "decoupler valve" in this paper). The control module component group to enable the control method using surplus pressure of primary pump is Table 1, and Fig.5 and Fig.6 are the module component group control flow charts. Fig.5 shows modules controlled by end pressure (Pe) and Fig.6 shows modules controlled by primary supply header pressure (Ps1). Under this control method, Fig.7 is a diagram showing correlation between the points of pipeline in a chiller plant system and the pressure value of each point in the pipeline. A chiller plant is located in the lower floor such as the basement in this diagram, and it shows the end load, air handling units installed in the most distant point, is located on the floors above the chiller plant in this case. The decoupler valve control adjusts the primary supply header pressure and increases a suction pressure on the secondary pump as much as possible (sown ih n (1), Fig.7). Then it adjusts the end pressure to the set-point by the inverter control of secondary pump (shown in (2), Fig.7). As a result, it enables to lower the inverter output and conveyance power energy consumption is reduced.

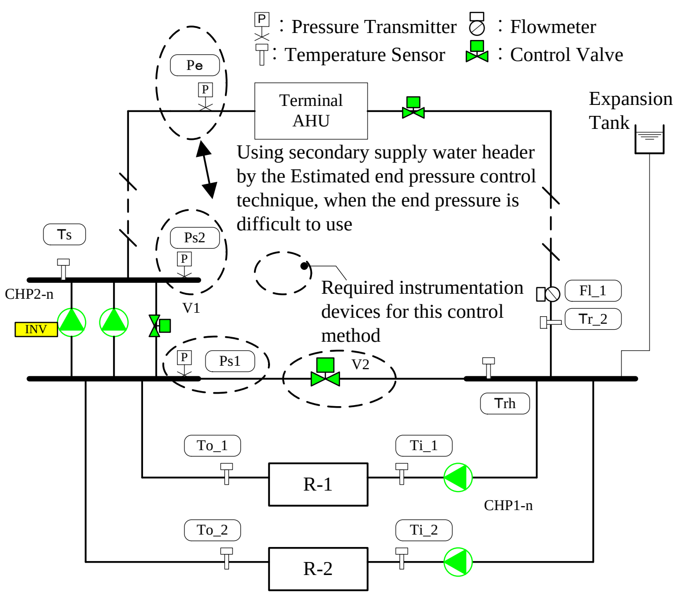

Fig. 4 Instrumentation Devices Required to the Control Method Using Surplus Pressure of Primary Pumps

Table 1: Control Point of Each Module

No.	*Control Module*	*Control Point*
1	*Inverter Control of Secondary Pump*	*End Pressure (Pe)*
2	*Number Control of Secondary Pump*	*End Pressure (Pe)*
3	*Pressure Relief Valve Control*	*End Pressure (Pe)*
4	*Decoupler Valve Control*	*Primary Supply Water Header Pressurure (Ps1)*

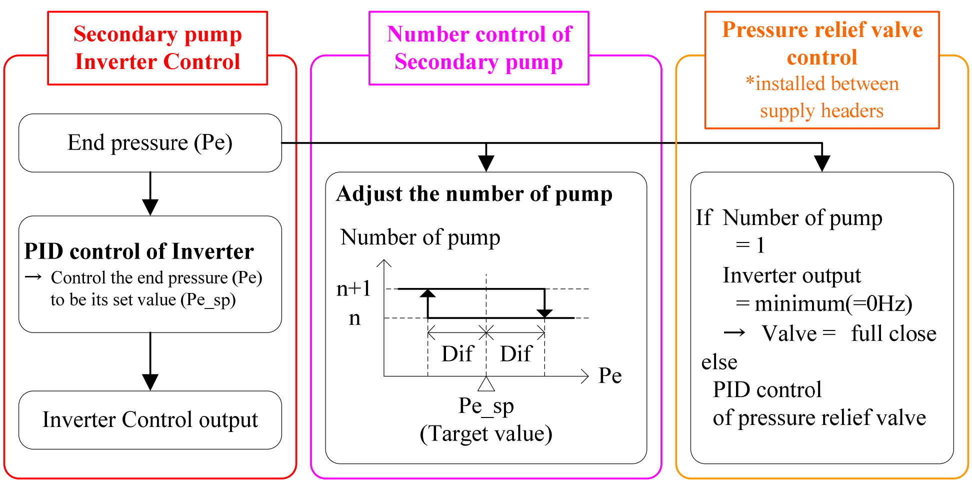

Fig. 5 Module Group Controlling by End Pressure (Pe)

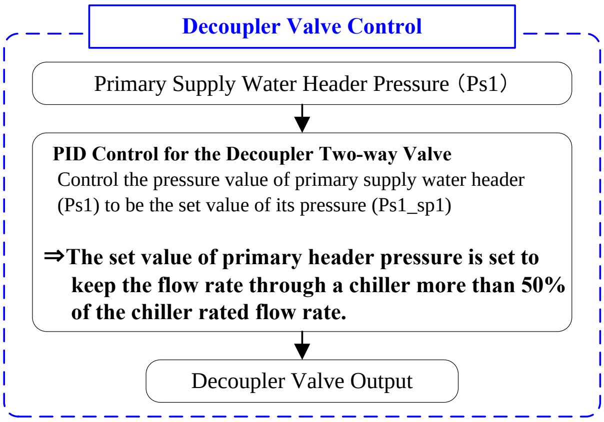

Fig. 6. Module Controlling by Primary Supply Header Pressure (Ps1)

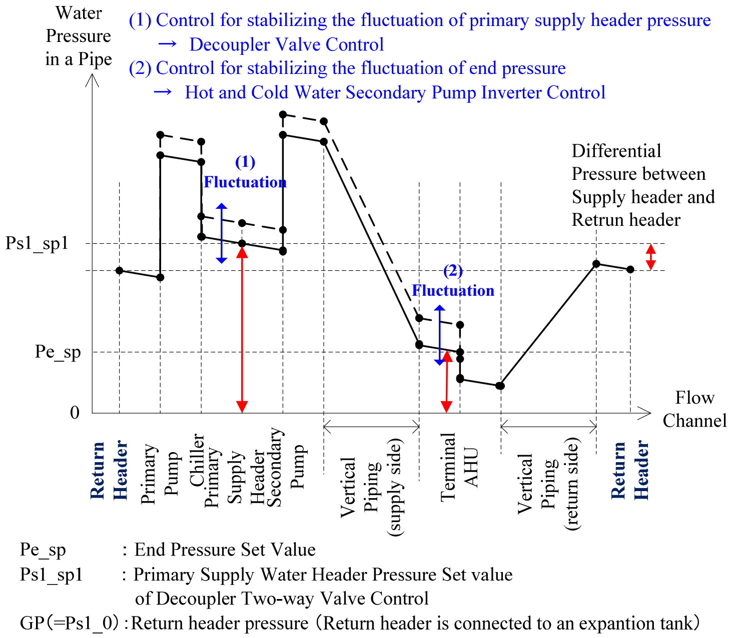

Fig. 7 Diagram about Each Pressure Value at Points of Pipeline in a Chiller Plant System

2.2 Each Control Module Details for the Control Method Using Surplus Pressure of Primary Pumps

(1) Decoupler Valve Control Module

This control module has two-way control valve and controls it for the primary supply header pressure (Ps1) to reach its target value (Ps1_sp1) by PID control. Generally, a role of primary pumps in the primary/secondary piping system is to keep a required flow rate for a chiller against the pressure loss of primary water flow loop. If the primary pump flow rate is more than the secondary one, in other words, the secondary loop flow is less than the rated flow rate of a chiller, the surplus flow returns to the chiller via a decoupler. (See Fig.8) In this situation, this control reduces the primary pump flow rate and raises its total head, if the decoupler valve is installed and appropriately adjusted. (See Fig.9) Accordingly, it enables to reduce the work of secondary pump owing to this surplus pressure. On the other hand, the chiller stops abnormally when the primary flow rate decreases too much because it is impossible to keep the minimum flow rate for the chiller operation. Therefore careful decision is required for the primary supply header pressure set-point under the decoupler valve control. It is required that the header pressure set-point of primary supply ensures a chiller minimum flow rate, even if all two-way valves at the secondary loads completely shut and the secondary side loop flow rate indicates “0”.

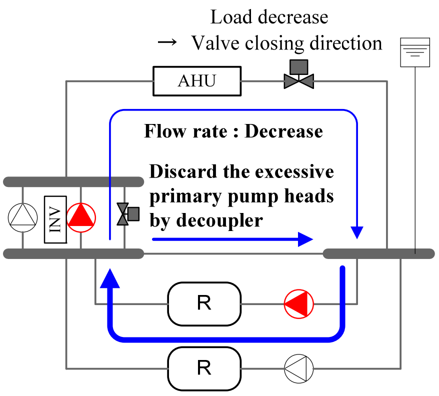

Fig. 8 Flow Situation in a Low Load Flow

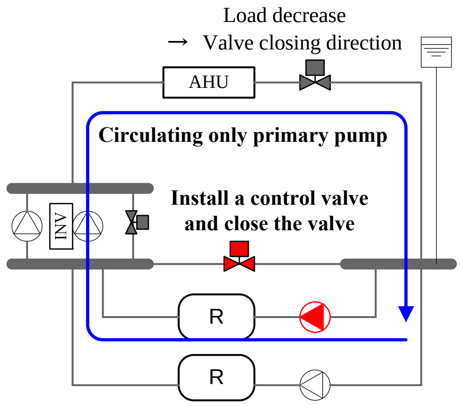

Fig. 9 Secondary Side Conveyance by the Surplus Pressure of a Primary Pump

(2) Inverter Control of Secondary Pump

Just as described in Section 1, the conventional inverter of secondary pump, the secondary supply header pressure, is controlled by supply pressure, and the set-point is set as a supply pressure value which is required for its designed maximum flow rate in most cases. As a result, an inverter frequency of secondary pump only decreases to around 35 – 45 Hz in many cases, since high set-point is kept even when the load flow is low. Therefore, the inverter is controlled by using end pressure of an inlet pipe point at the most distant air handling unit, instead of the supply pressure, since the most distant air handling unit is maximum pressure loss on the route in cool water conveyance from the chiller plant systems. If the differential pressure between inlet and outlet at the most distant air handling unit can be ensured enough flow rate, all other air handling units can be also ensured their required pressure. Consequently, this control can supply to the secondary loop flow its appropriate pressure depending on the load flow change. The conveyance power of the secondary pump can be significantly reduced by using the primary pump surplus pressure for secondary side water conveyance and reducing inverter output of secondary pump largely, if the decoupler valve control module described in (1) is used together with this inverter control of secondary pump after changing it as seen above.

(3) Number Control of the Secondary Pump

Existing control of the secondary pump controls the number of operation units by its secondary flow rate (load flow rate). For example, when the secondary flow rate becomes more than the rated flow rate of one secondary pump which is usually set-point of increase step from one to two, the number of secondary pump increases from one to two. Since suction pressure of secondary pump is changed by the decoupler valve control in the new control method which we developed, the flow rate which one secondary pump can flow changes. It means the flow rate is more than its rated flow rate of a secondary pump when the suction pressure is increased by the surplus pressure of primary pump. Therefore the number control of secondary pumps is decided by the end pressure instead of the secondary flow rate. The timing chart of control performance by this method appears in Fig.10. The control method is illustrated by using this figure as following. Normally, the end pressure (Pe) decreases if the flow rate on the secondary side increases in conjunction with the load. As the load is going to increase further, the end pressure cannot keep the target value (Pe_sp) and decreases even if an inverter output is maximum value. Secondary pumps are increased by this control method when this end pressure decreasing that we described above becomes lower than the increasing threshold value (Pe_sp−Dif_sp1). On the contrary, secondary pumps are decreased when the end pressure becomes higher than the threshold decreasing value (Pe_sp+Dif_sp2).

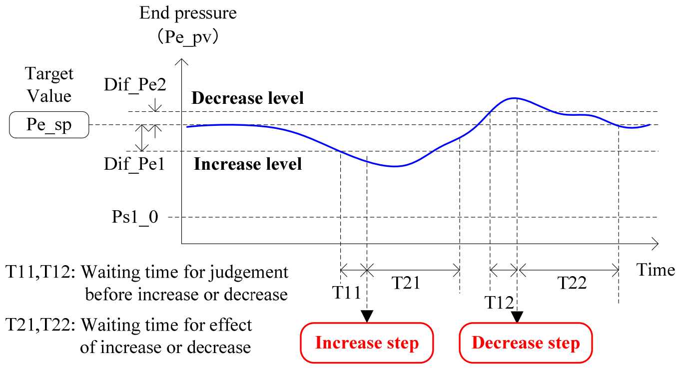

Fig.10 Time Chart of Secondary Pump Number Control

3. Installation to Verify

3.1 Installation Site

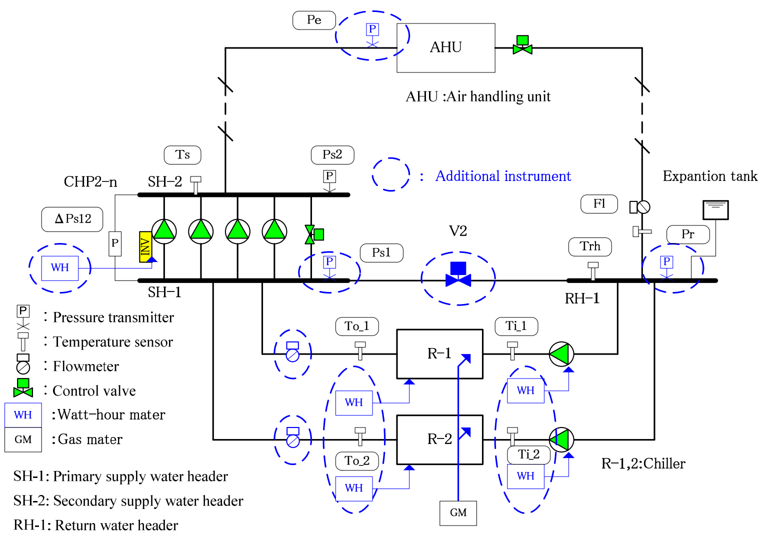

Fig. 11 Instrumentation Diagram of Chiller Plant System

We installed a system with "the control method using surplus pressure" in an actual site to have an effect verification. The site is "Ritsumeikan Uji Junior and Senior High School" located in Uji-shi, Kyoto, Japan and it has four floors above ground with total floor space of 19,172 square meters. A primary/secondary piping system provides as its air-conditioning system and it has two units of "gas fired double effect absorption chiller heaters" with 1,582 kW cooling capacity. ("Gas fired double effect absorption chiller heaters", i.e. "gas absorption chiller heater") Four units of hot-cold water secondary pump are in the system and one of them is an inverter. The inverter unit makes variable flow operation. Loads are air handling unit (AHU), outdoor air handling unit (OHU), and fan coil unit (FCU). Fig.11 is an instrumentation diagram of chiller plant system and main equipment specification appears in Table 2. Pressure transmitters are installed at the inlet piping of FCU located at end point, primary supply water header of primary pumps, return water header, and two-way control valve are installed in decoupler. For the verification of effects using this control method, measuring instruments are also installed to measure "its flow rate through chillers" and "consumption energy of each equipment".

Table 2: Main Equipment Specification of the Chiller Plant

Name of equipment	*Specification*
Gas absorption chiller (R-1, R-2)	*Freezing capacity : 1,582kW , Cool water flow rate : 3,240L/min,*
	Cool water temperature: 14-7 ℃,
	Cooling water flow rate : 7,400L/min , Cooling water temperature: 32-37.5 ℃
	Rated gas consumption : 123m^{3} (N)/h
Primary cool water pump (CHP-1,2)	*Rated flow rate : 3,240L/min , rated head : 150kPa , rated shaft power : 15kW*
Cooling water pump (CDP-1,2)	*Rated flow rate : 7,500L/min , rated head : 200kPa , rated shaft power : 15kW*
Close-type cooling tower (CT-1,2)	*Cooing Capacity : 2,878kW (Outdoor air : 27 ℃WB) , Circulationg water amount : 7,500L/min , Temperature of cooling water temperature : 37.5-32 ℃, Rated power consumption of the fans : 5.5kW×3*
Secondary water pump (CHP-3,4,5,6)	*Rated flow rate : 1,620L/min , Rated head : 300kPa , Rated shaft power : 15kW*

3.2 Situation Analyses before Introducing the Control Method

We analyzed data of air-conditioning period, during June to September, 2008, for the situation understanding before introduction. Fig.12 shows an occurring frequency distribution of load flow rate and Fig.13 shows an occurring frequency distribution of secondary pump inverter output, and Fig.14 shows an occurring frequency distribution of Delta-T of primary loop (difference between inlet temperature and outlet temperature of chiller) and secondary loop (difference between secondary supply temperature and return temperature). The inverter output value in this figure assumes that 60 to 0Hz is 100 to 0%. As will be noted from the Fig.12, the percentage of load flow rate that becomes less than 1,620L/min is 97%. 1,620L/min means a rated flow of a secondary pump. Therefore it turns out load flow rate is mostly covered by a secondary pump. The rated flow rate of one chiller unit, the rated flow rate of primary pump, is 3,240L/min. Since the load flow rate is constantly less than half the percentage of 3,240L/min, it is considered that at least 50% water conveyance of primary pump is returned to decoupler. As you see Figure-14, the frequency that the temperature difference on primary loop Delta-t becomes less than 3K is 85%, whereas the frequency on secondary loop Delta-t stays only 40%. Since the average temperature difference on primary

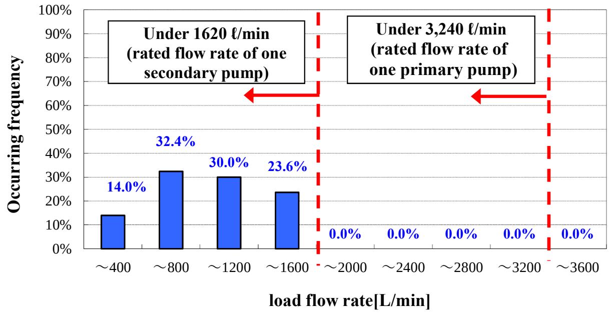

Fig.12. Occurring Frequency Distribution of load flow rate (before introduction)

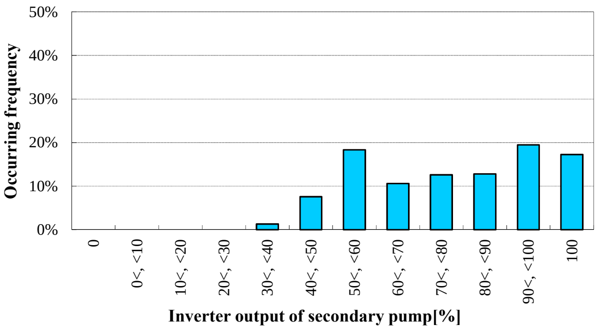

Fig.13. Occurring Frequency Distribution of Inverter Output (Before introduction)

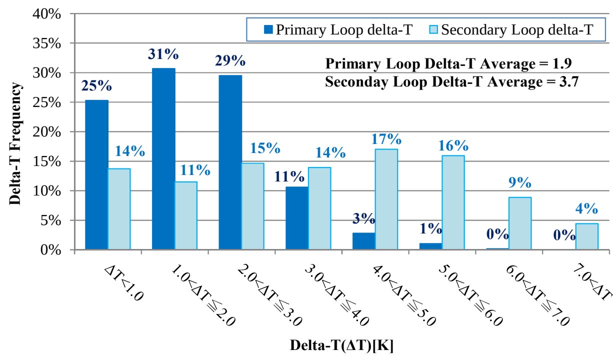

Fig.14. Delta-T Distribution between Primary Loop and Secondary Loop before introduction (June to September, 2008)

loop is 1.9K and the average temperature difference on secondary loop is 3.7K, it means primary loop average is a half of secondary loop average; the maximum thermal load is only about 50% of a chiller capacity. Therefore, it is inferred chiller runs in an inefficient low load operation. Fig.13 shows the inverter output is controlled in 40%-100%. The occurring frequency becoming less than 800L/min is 55%. (800L/min means half percentage because the rated flow rate of secondary pump is 1620L/min.) However the rate that the inverter output becomes less than 50% is only about 10%. Additionally, the case that the inverter output becomes less than 40% had not appeared. As described in chapter 1, “Summary and Problems”, it shows the inverter output does not be under a certain value, because it is required the setting value of water conveyance pressure is kept to satisfy a designed maximum flow rate even if the load flow rate is low.

3.3 Evaluation after Introducing the Control Method

Occurrence frequency appears in each figure as following, Fig.15 shows occurrence load flow rate before or after introduction, Fig.16 shows inverter outputs, and Fig.17 shows power consumption of conveyance pumps. Fig.15 and Fig.16 show inverter outputs of secondary pump are lowered sharply, despite the load flow increases significantly as compared to 2008 (Before introduction) and 2010 (After introduction). As a result, the power consumption of secondary pump was reduced by 93%. The 0% （0Hz） inverter output, as shown in Fig.16, means secondary pump is not operated substantially and all conveyances, both primary conveyance and secondary conveyance, can be covered by only primary pump. It accounts for 37% of the occurrence frequency. In addition, both of secondary pump with inverter and without inverter run idle, when the inverter output of secondary pump is 0, all the other secondary pumps without inverter stop, and only primary pump operates. In point of the pump without inverter running idle, there is no problem because electric voltages are not energized to the standard motor. On the other hand, even if the motor with an inverter is 0% (0Hz), there are concerns about the potential of heat generation since voltages are applied to the motor and it acts as a regenerative brake. However, we think the potentials that the power is applied to the pump as a regenerative brake are extremely low because the discharge flow rate of primary pump is distributed to multiple secondary pumps. Through this test period, the occurring frequency of 0% (0Hz) inverter output of secondary pump was occupied

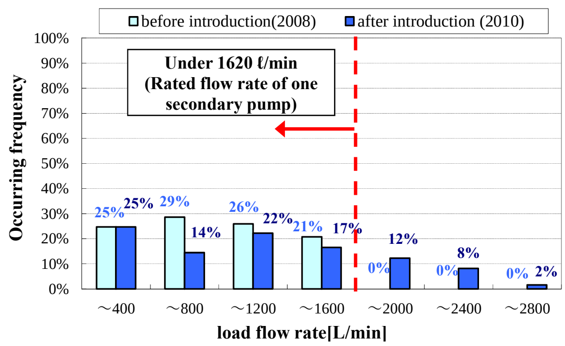

Fig.15. Occurrence load flow rate before or after introduction

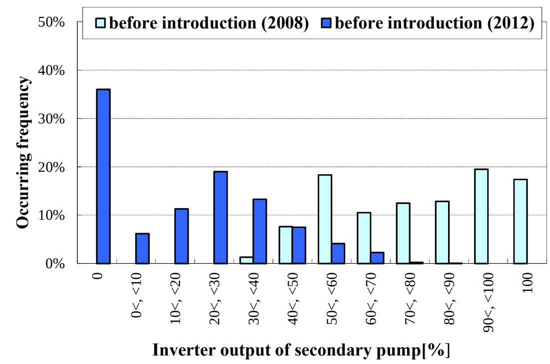

Fig.16. Occurrence Inverter Output of Secondary Pump Before or After Introduction

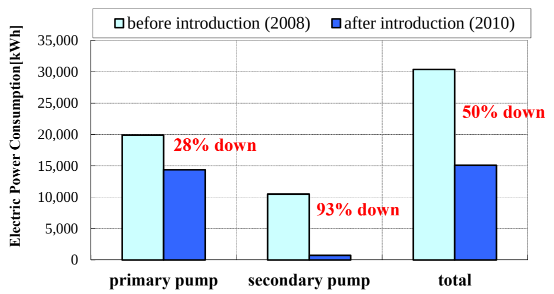

Fig.17. Power Consumption of Conveyance Pumps Before or After Introduction (from June to September)

45% as noted above, but any problems did not occur. We have more evaluation tests in this point hereafter. As shown in Fig.17, the power consumption of primary pump was reduced 28% as with the secondary pump. It can be considered by this result that the power consumption of primary pumps was reduced as much as chiller flow rate was reduced by controlling decoupler valves. 50% reduction of the power consumption was made by both the primary pumps and secondary pumps. Fig.18 shows each an occurring frequency distribution of Delta-T of primary loop and secondary loop and primary loop, as a comparison before and after this control method introduction, which is from June to September in 2008 and same period in 2010. As you see left figure of Fig.18, Delta-T of primary loop largely increased from 1.9K (2008) to 5.2K (2010). Although it is small increase, right figure of Fig.18 shows that Delta-T of secondary loop also increased. As you see Fig.19, the primary loop flow after introduction decreased compared to before introduction (in 2008) by the operation of decoupler valve control. Whereas the primary flow rate in 2008 is approximately constant between 3200 and 3400 L/min, the most frequent flow rate in 2010 was 2400 to 2800 L/min. As a result, the increase in Delta-T of primary loop is thought to be due to the reduction of primary flow rate. The reduction of energy consumption by improvements of chiller operational efficiency is much expected when Delta-T of primary loop increases.

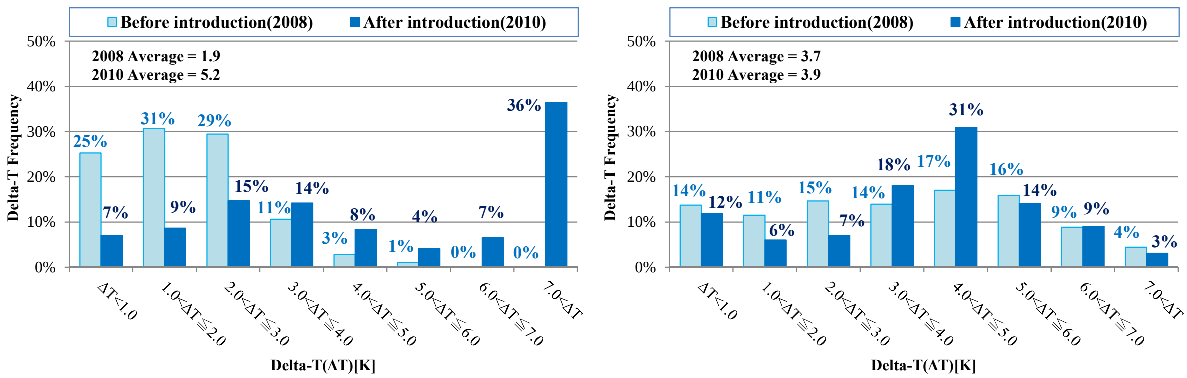

Fig.18 Delta-T Distribution as a Comparison between Before and After Introduction
(Left : primary loop, Right : secondary loop)

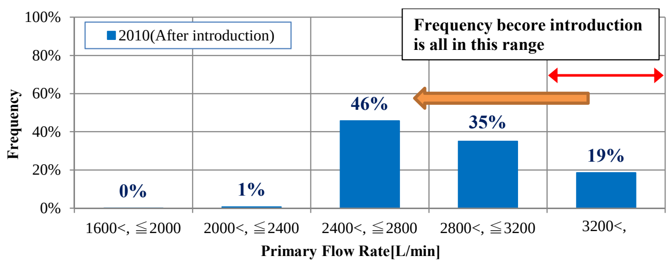

Fig.19 Flow Rate Distribution of Primary Loop after Introduction (June to September)

3.4 Application Condition of This Control Method

This instance is an excessive case such as an actual cooling peak load is less than 50% capacity of a chiller even in the summer maximum load period. Even if the case is extreme, this control method is fundamentally effective for the chiller plants which consist mostly of the partial load operation. The specific applicable condition of this control method is following three points shown in Fig.20;

1) All Primary pumps are constant-speed pumps.

2) At least one secondary pump has inverter, and variable speed control is available.

3) The condition that an actual load is less than a chiller capacity occurs frequently. Especially the case is effective that an actual load is far below its capacity at the time like less than 50% of capacity. Similar case occurs frequently in the office buildings, though the load difference is small in the factories throughout a year.

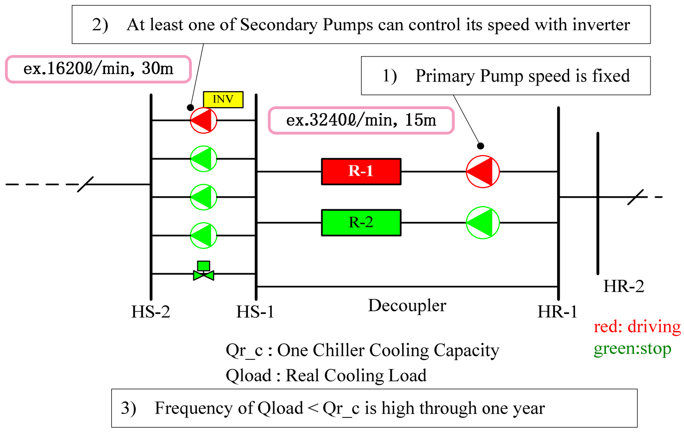

Fig.20 Effective Condition in using the Control Method Using Surplus Pressure of Primary Pumps in Chiller Plant System

4. Extension of Using the Control Method Using Surplus Pressure of Primary Pumps

4.1 Analysis of Differential Pressure on Secondary Side

The differential pressure on secondary side indicates the difference between secondary supply header and return header. It is, therefore, differential pressure of whole water conveyance on secondary side. Fig.21 is a distribution map which shows a correlation between the load flow rate and the differential pressure on the secondary side from June to September. It shows the maximum load flow rate during this period is 2,700L/min which is approximately 83% of the rated flow rate per chiller (3,250L/min). The figure also shows the differential pressure is higher than 70kPa through the whole flow rate, which is a differential pressure value required for total load flow rate (6,480L/min=3,240L/min×2) that is confirmed by this verification experiment. In fact, when the load flow is at least less than 2,700L/min, the secondary pump is no longer required and the superfluous differential pressure is supplied to the secondary side by only operating the primary pump as well. For this reason, further reduction of conveyance power is expected by introducing an inverter to a primary pump and controlling it appropriately.

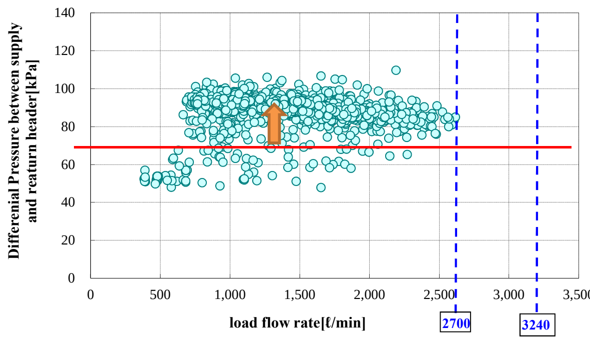

Fig.21 Distribution Map about Correlation between the Load Flow Rate and the Differential Pressure on the Secondary Side from June to September in 2010

4.2 Further Extension of the Control Method Usage

We suggest a countermeasure as handling for the secondary side differential pressure becoming excess by only the primary pump operation. The mechanism is to install an inverter to a primary pump and this inverter is controlled only when the secondary pump is no need to operate. The inverter output of primary pump is fixed around its rated speed when the secondary pump operation is required. When the secondary pump operation is not required, the primary pump inverter is controlled to maintain its appropriate pressure at the secondary side and to secure the smallest chiller flow rate at the same time. When the secondary pump is not required, the controller stops the secondary pump inverter control, and switches from the secondary pump inverter control to the primary pump inverter control. Fig.22 and Fig.23 show the flow chart about the primary pump inverter control.

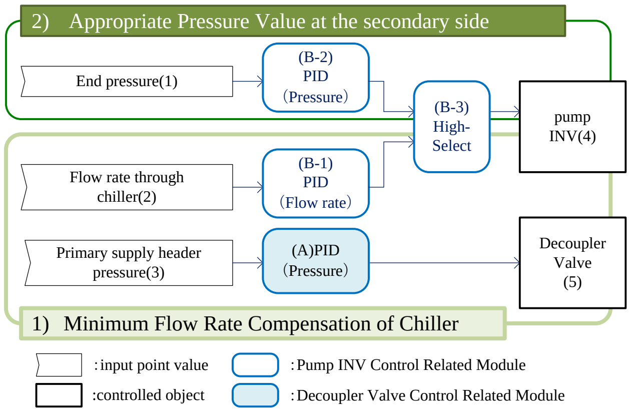

Fig.22 Control Module Constitution at the Time of the Second Pump-free Judgment

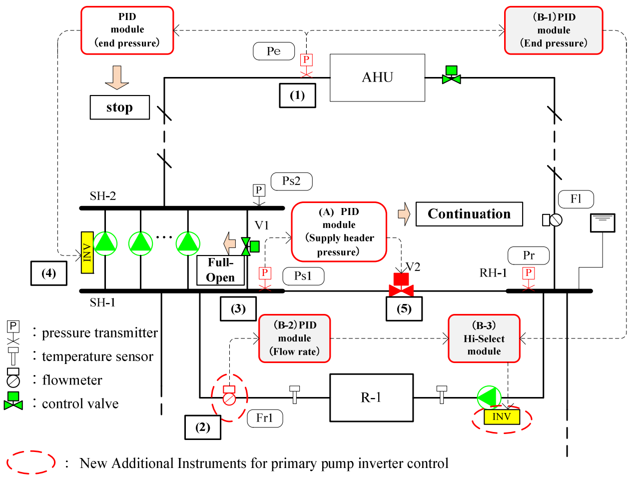

Fig.23 Control Flow at the Time of the Second Pump-free Judgment

1) Stop the secondary pump inverter control. Continue the decoupler valve control with no change.
2) Full-open the bypass valve between secondary supply header and primary supply header.
3) Start the primary pump inverter control. The final inverter output value is decided by high-selecting the result of PID output by the end pressure and by flow rate through chillers in this control.

The secondary pump can stop completely by using the control method that we described, if the actual peak load is lower than expected and can be covered by the primary pump head.

Conclusion:

Since the 1990s, the primary/secondary pump system whose secondary flow fate rate is ever-changing by controlling with two-way valves on the load side is introduced into many buildings. If the primary pump of chiller plant system for this project happened to be designed by over-capacity, downsizing the primary pump to a proper ability was one of the countermeasures. However the primary pump size was selected properly to meet a rated flow rate of a chiller. In other words, it is possible to describe as a result that whole chiller plant system including a chiller was designed excessively instead of a primary pump. There are many cases that a real peak load is much smaller than a design expected peak load and the capacity of chiller plant system has been accordingly excessive against the actual load. In such cases, it is highly possible that the conveyance power can be dramatically reduced by introducing our “Control Method Using Surplus Pressure of Primary Pumps”. In addition, this control method is available by only installing a two-way valve in decoupler on an existing chiller plant system and newly installing pressure sensors at primary supply header and the inlet of distant load, air conditioning. As a result, it shows the installation can be achieved at low cost and it is a cost-effective countermeasure against energy saving. An inverter did not be installed to the primary pump in this instance. However, we consider from this report that significant energy reduction is possible by using this control method after the inverter installation to a primary pump.

Reference:

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The potential and challenges of monitoring-supported energy efficiency improvement strategies in existing buildings

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Abstract:
The ongoing EU-supported CAMPUS 21 explores the energy efficiency potential of integrated security, control, and building management software. The main objective of the project is to compare the energy and indoor-environmental performance of a number of existing facilities before and after real or virtual implementation of monitoring-based control improvement measures.

Keywords:
Building Control, Building Systems, Building Operation

1. Introduction

This paper reports on an ongoing project titled "Control & Automation Management of Buildings & Public Spaces in the 21st Century" or CAMPUS 21, which explores the potential of integrated security, control, and building management software systems in improving the energy efficiency of buildings (CAMPUS 2011). The project involves participants from both academic institutions and industry and is supported by the European Union (EU 2012). The premises of the project are as follows:

- In most European countries, existing buildings represent, in terms of volume and energy use intensity, the dominant part of the overall building sector. They should be thus specifically targeted for energy efficiency improvement.
- Through the improved integration of various existing monitoring, security, and access control systems the operation of building control systems can be improved.
- Energy efficiency measures are urgently needed and are of utmost importance in view of ecological and economical sustainability.
- Improving facilities' energy efficiency may not compromise their functional and indoor environmental performance. Ideally, it should go hand in hand with an improvement of indoor environmental quality and services.

To clearly illustrate the project's approach, it is useful to consider the main ways and means to improve buildings' energy efficiency. Generally speaking, a distinction could be made between hardware-centric and software-centric approaches. The hardware-centric approach focuses on the improvement potential of the physical aspects and components of buildings and is not the major focus of the project. On the other hand, it could be argued that the operation of existing buildings often involves inefficiencies that may be labeled as software-related, in that they are due to poor integration of existing IT-systems, including the insufficient interoperability of the underlying data and information processing models. This information-centered aspect represents the main focus of the aforementioned CAMPUS 21 project and this paper. It can be formulated in terms of the project's initial hypothesis: *Utilization of existing buildings' historic and run-time monitoring data (energy use, indoor environment) and the integrated analysis of this data can help to improve energy efficiency through the optimization of buildings' operational regime.*

While the postulate appears plausible (O'Donnell 2009, Raftery et al. 2010), both solid implementation guidelines, advanced benchmarking criteria, and extensive empirical evidence are needed to further promote and popularize the pervasive use of monitoring toward energy efficiency improvement efforts in buildings.

2. Approach

Within the overall framework of the CAMPUS 21 project, a number of steps will be undertaken to facilitate the examination of the above hypothesis:

- Three functionally and morphologically different building complexes in three different locations (Germany, Ireland, and Spain) are selected.
- The buildings' status quo is documented.
- The comparison of the existing and desirable monitoring infrastructures in the existing buildings enables the identification of required supplementary monitoring components. Thereby, alternative options are to be considered and evaluated (i.e., augmentation of existing BMS versus establishing a parallel monitoring grid).
- The facilities' monitoring infrastructure is to be upgraded based on the outcome of the previous step and under consideration of available resources.
- A systematic analysis of data models is to be performed. Thereby, possibilities for the development of an integrated data model shall be explored, which could effectively support the documentation, benchmarking, and operation of building services.
- Given upgraded monitoring infrastructures, an initial monitoring phase is to deliver a signature of the selected facilities in view of their current level of energy and indoor environmental performance.
- Based on a thorough analysis of data collected in the previous step, recommendations and specific measures toward improving the operation schemes of the respective facilities can be developed. Specifically, data pertaining to occupancy, weather conditions, loading level of available thermal storage elements, etc. could be utilized to mine possible inefficiencies in the current operational practices in the selected complexes.
- Subsequent to modifications of the control processes, a second extended monitoring phase is to document the post-modification performance of the facilities.
- Comparison of the performance of the facilities before and after the implementation of monitoring-based control improvement measures shall provide reliable data for the evaluation of the initial hypothesis.

In the following, we address the work and progress within the initial phase of this project towards achieving the above targets. Specifically, we discuss the relevant performance indicators, monitoring strategies, demonstrator facilities, gap analysis concerning existing facilities' monitoring infrastructures, operational improvement scenarios, and future research plans.

3. Kinds and levels of monitoring

3.1. Performance indicators

As noted earlier, the central objective of the research project presented in this paper is improving the energy efficiency of existing buildings via utilization of relevant monitoring data. It is important to stress that such data is not limited to buildings' energy performance alone. From a global perspective, a system's efficiency is a function of services it provides and the resources it uses. In case of buildings, it can be argued that the indoor climate is the primary service provided, whereas the primary resource used is energy. Proper assessment of buildings' energy efficiency must thus include, at a minimum, energy metering and indoor climate monitoring (resource use category may also include other resource-related and environmental implications of buildings' operation).

3.2. Categories of data

There is no definitive standard for assessing and amending the monitoring infrastructure of existing buildings' data monitoring infrastructures. In fact, given the variety in buildings' type, age, size, and construction styles, and given differences in the level of integration and sophistication of buildings' technical systems, compilation of a general guideline may not be a trivial task. For the purposes of the present research, previous experiences were drawn upon to set up a generic scheme for monitoring domains and levels. Data to be monitored are differentiated in terms of four categories, namely energy use, indoor environment, internal processes, and external boundary conditions. The energy use category involves a further differentiation: Energy monitoring needs to be conducted for multiple energy systems (e.g., thermal, electrical). Moreover, to the extent possible and feasible, high levels of temporal and spatial resolution should be targeted. Temporal resolution denotes the polling frequency of energy metering of various systems. Spatial resolution denotes the extent of existing sub-metering for different parts of a building (per floor, per space, per workstation, etc.).

The indoor environment monitoring category typically addresses parameters that are relevant for the health and comfort of the occupants. Such parameters often represent the target of the building operation process (e.g., indoor air temperature, relative humidity). The internal processes category refers to the presence and activities of the occupants as well as to the position (state) of devices that can be controlled by occupants or the building's control system (Mahdavi 2011). The external boundary conditions denote mainly the weather conditions in vicinity of a building. A dedicated weather station would represent the most straightforward way to collect data pertinent to this category. Such data is critical, if the energy and indoor environmental performance of a building are to be properly evaluated.

3.3. Levels of monitoring

The realization of a new monitoring infrastructure or upgrading of an existing one in a building depends of course on the availability of resources for hardware and software. In the course of CAMPUS 21 project, it was found useful to consider three different levels of monitoring. Simply stated, these levels could be labeled as minimal (M), default (D), and high-end (H). A possible specification of these levels is captured in Table 1.

Table 1. Proposed monitoring levels M (minimal), D (default), and H (high-end) for data monitoring categories energy, indoor environment, internal processes, and external conditions. In this table, θ_{air}: air temperature; RH: relative humidity; E_{glob}: global horizontal irradiance; E_{diff}: diffuse horizontal irradiance; E: illuminance; CO_2: carbon dioxide concentration; v_s: air flow speed; v_{dir},: wind direction pa: atmospheric pressure; prec.: precipitation.

Monitoring data category	M	D	H
Energy use	One meter per building for selected energy sources	1 per floor (or section/block)	1 per room (or workstation) for all energy sources
Indoor environment	θ_{air}	θ_{air}, RH, E, CO_2	θ_{air}, RH, E, CO_2, v_s
Internal processes	One sensor per typical (representative) zone	Sample of zones/occupants	All zones/occupants
External conditions	θ_{air}, RH, E_{glob}, v_s, v_{dir}	θ_{air}, RH, E_{glob}, v_s, v_{dir}	θ_{air}, RH, E_{glob}, E_{diff}, E, CO_2, v_s, v_{dir}, p_a, prec.

3.4. Sensor specification and data formats

Documentation of the existing and projected monitoring infrastructure and communication of monitoring data represent a common challenge in building automation. A typical problem lies in the difficulties to obtain data from existing building automation systems' often proprietary data processing units. In the initial project phase, communication of existing sensor types and locations as well as historical sensor data are approached in a very simple (flat) manner.

4. Demonstrator facilities

To explore the potential of the project's ideas and objectives in a hands-on manner, three "demonstrators" (existing building complexes) were selected. The first demonstrator, UCC, is a university in Ireland. The second and third buildings, Huerta del Rey in Spain and Commerzbank arena in Germany, are sport facilities.

4.1. UCC Campus, Cork, Ireland

University College Cork (Ireland) has 120 educational, research, and sports buildings of varying age spread over approximately 33 hectares excluding playing fields. Two specific buildings in the campus (CEE, ERI) and its energy network are considered for the purpose of project explorations.

CEE Building

The Civil and Environmental Engineering Building is situated on Main Campus, adjacent to College Road. The building was completed in 1910. The building was initially used to accommodate the college's physics and chemistry laboratories and its construction is typical of many buildings constructed across a range of institutions in Ireland during the early twentieth century. The building is naturally ventilated and heated by iron cast steel radiators fed from the campus CHP (Combined Heat and Power) system. A major retrofit was undertaken in 2009/10 to improve energy efficiency and provide a full Building Management System and wireless monitoring.

ERI Building

The Environmental Research Building is situated on the west of Cork city, on the Lee Road. The ERI is not part of the main campus but provides a demonstration site with renewable energy sources such as solar thermal and geothermal systems. In addition, it is supplied with gas for hot water boilers and electricity from the national grid for lighting and other electro-mechanical systems. The building was inaugurated in 2006. The two buildings chosen provide a strong contrast in design type, condition, and age.

4.2. Huerta del Rey Sports Centre, Spain

The Huerta del Rey Sports Centre (Valladolid, Spain) was built in 1975. It consists of indoor facilities (sports hall, indoor swimming pool, gym, fitness room), offices for the Municipal Sports Foundation, and a bar. The outdoor area includes two tennis courts, six paddle tennis courts, one football field, three parking lots, and a sunbathing area for the indoor pool.

4.3. Commerzbank Arena, Frankfurt, Germany

The soccer stadium Commerzbank Arena is located in suburbs of Frankfurt near the Airport. The stadium was build in five phases over three years (2002 – 2005). The stadium has the largest moveable steel-rope-membrane cover in the world. It can be closed within 15 minutes. The stadium is usually used by the soccer club "Eintracht Frankurt". It also hosts concerts and business events. In addition to the standard facilities of a soccer stadium, the Arena hosts special VIP areas with Lodges as well as meeting and event rooms. These areas can be used both in conjunction with the scheduled games and, independently, for special business events.

5. Gap Analysis

The three demonstrators were analyzed to find the extent of the available monitoring infrastructure and if it would allow for a detailed performance evaluation. The initial assessments suggest that the existing monitoring systems do not have the scope to support a detailed evaluation of the buildings' operational processes and alternative (improved) control approaches.

5.1. UCC Campus

The UCC campus provides different types of building automation, security, monitoring, and management systems. There is no real integrated management system for the entire campus. At the campus macro-level, energy use data is monitored and associated trends analyzed. Weekly reports are produced and distributed to all staff for energy awareness. At the micro or building level, the quantity of available data varies from building to building. Currently, hourly campus wide energy data is available for electricity, gas, and water usage.

The CEE Building is equipped with a building management system and a thermal energy meter to monitor the overall energy use. But it does not have a real capability for sub-metering. BMS system data is currently not easily accessible. Most parts of the lighting system are controlled by PIR-sensors or the available daylight. In 2009 the building was upgraded with a wireless system to monitor indoor environmental conditions.

The most extensively monitored building of the UCC campus is the ERI Building. It provides a database for historical data with a simple web interface. There is a large dataset of records from wired and wireless sensors and meters throughout the building available to CAMPUS21 researchers. This data has been collected over a period of 5 years for use in another research project titled ITOBO (Information and Communication Technology for Sustainable and Optimized Building Operation).

5.2. Huerta del Rey Sports Centre

The building and control systems of this sports center are, in accordance with its age, very simple. The building has experienced a few updates, such as the integration of a solar hot water plant on the roof and the replacement of the original lighting system. The main deficit of this demonstrator is the lack of an overall building management and control system. There is only a small automation unit associated with general building systems for heating, ventilation, and hot water supply. This unit is used for the basic control of these systems. The control of the zone devices for heating, ventilation, and lighting is done manually. Given the simplicity of control system, no monitoring data of user actions and internal conditions is stored. In addition to the general building system, some zones were equipped with independent air-conditioning (split) units. The interaction with these systems is not monitored or even integrated in the overall control system. Updating the general monitoring system would be, in this case, essential for the evaluation and further improvement of the building's control system. Additional indoor climate sensors, a weather station, and an energy sub-metering system for relevant energy flows are needed.

5.3. Commerzbank-Arena, Frankfurt, Germany

The Commerzbank-Arena is equipped with a modern BMS system. This system is used for the general operation of the HVAC and Lighting systems. A centralized management system is implemented but it does not support any monitoring of indoor conditions, outdoor climate, or energy flows. To meet the project's requirements, data storage capability must be augmented and detailed sub-metering must be implemented. Depending on the optimization scenarios, adaptions of actuators and sensors are necessary.

6. Control System Optimization at Campus21

A general design for an active control system optimization was developed for the Campus 21 Project. The optimization is to be achieved primarily via manipulation of set points and schedules. Figure 1 shows this overall optimization approach in the Campus21 project.

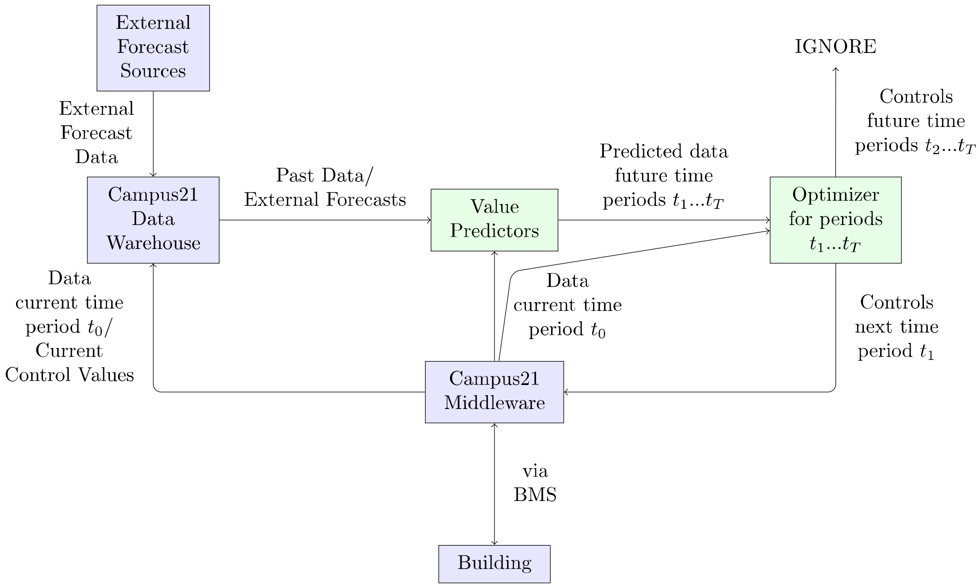

Figure 1: System design for optimization

The optimization works in the following way. Current building data are accessed through the BMS (Building Management System) and the Campus21 Middleware. Historical data can be accessed on the Campus21 Data Warehouse, with communication passing through the middleware. Information from external forecast services is stored in the data warehouse on a regular basis, again communicating through the middleware. Value Predictors, which based on past, current, and external data produce forecasts for system elements over the optimization horizon. The Optimizer, which computes control decisions from the available measured and predicted data produces control values for all time step $t_1...t_T$ of the prediction horizon, but only values for the next time period t_1 are passed back to the BMS through the middleware, all later values are ignored. In the next time step, the whole process is repeated. This receding horizon always produces the set points for current operation, while optimizing the results over the entire optimization period.

The proposed design will be used for all scenarios within the Campus 21 project. Virtual Studies for the CHP plant scenarios at UCC Campus and Commerzbank Arena will use an adapted design for the simulations.

6.1. Optimized control and load shifting for building systems

UCC ERI Building

At the UCC Environmental Research Institute building an optimized building system control will be implemented. A simplified optimizer model (see Figure 2) was developed based on the physical models and the related energy flows. The model consists of the main energy sources such as Solar (S), Gas (G), and Electricity (E) together with distribution and storage system.

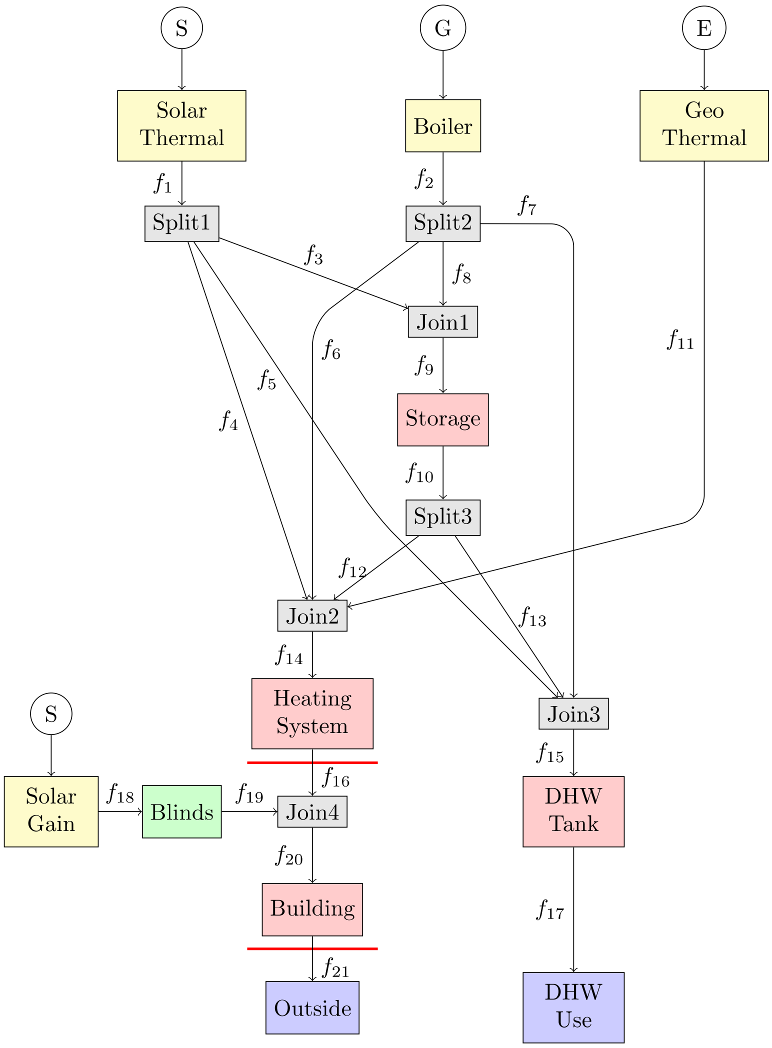

Figure 2: System model for optimized building systems control in the UCC ERI Building

Huerta del Rey Sports Centre

Heating Energy sources at the Huerta del Rey Sports Centre are a solar thermal array on the roof and two gas boilers (treated as a single device within the model). The solar array can be used to either heat the swimming pool (small and large pool are treated as a single element in the model), or to heat water in the storage tanks, which at the moment can only be used to preheat water for DHW (Domestic Hot Water). The boilers can be used to heat the swimming pools, or heat the DHW to the required temperature level. The boilers also feed the air handling units and the building heating system. However, these elements are not considered at the moment. The pools loose heat to the pool space, while hot water is used in the swimming pool area and the sports hall. There is a potential link between the storage tanks and the pool heating, which is currently not used, but which would offer more optimization opportunities.

Figure 3 shows the energy flow model for the Huerta Del Rey sports center in Valladolid. S donates the Solar source and G stands for Gas.

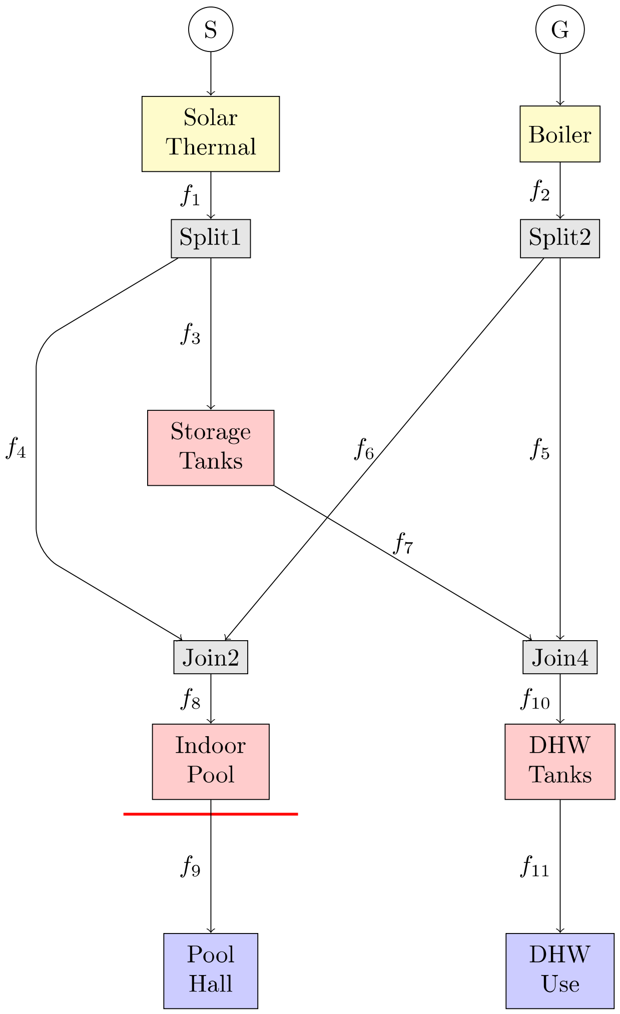

Figure 3: Overall system design for Huerta Del Rey sports center.

6.2. Load Shifting and optimized CHP plant operation

UCC Campus

As the current agreement on electricity tariffs for the UCC CHP plant runs out in 2014, it is interesting to consider the impact of different tariff models on the operating cost of the CHP plant in the future. For this purpose, we can run the UCC campus model with different alternative pricing models on the same forecasted demand profiles and compare total operating costs as well as operating hours of the equipment and total greenhouse gas production.

The demonstrator will produce schedules for the operation of the CHP plant, which can then be checked by UCC Building and Estates and the plant operator for feasibility. The schedules produced will not be actually tested as long as the current operating scheme is running.

The CHP plant delivers both heat and electricity. Backup gas fired boilers can augment heat production. The produced heat is used to satisfy consumer's demand. Hence we may need a heat dump to release unneeded heat, if the CHP unit is producing more than required. The electric output of the CHP plant goes to a switch which redirects all output to the grid, while satisfying the internal demand from the grid. In simulations we can explore other operating modes of the switch to compare the resulting price structure. Both heat and electricity consumers are represented by single sink component, we do not differentiate between the different users on the campus and predict only total consumption. Figure 4 illustrates the corresponding model for a virtual implementation.

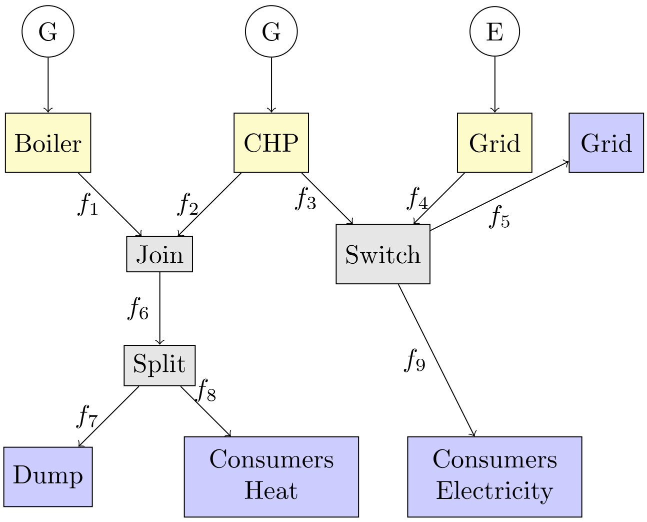

Figure 4: UCC Campus System model for CHP operation optimization.

CHP System at the Commerzbank Arena

This demonstration scenario is based on the idea of replacing the existing power plant with an CHP plant. The objective of this scenario is to estimate the total cost of operation of a CHP plant installed in the stadium, compared to the cost of operation using the existing or a replacement boiler in the current operational design. This could provide a more accurate picture of potential savings than can be achieved with a CHP plant, thus helping to determine if such an investment would make sense for the Commerzbank Arena. Figure 5 illustrates the associated model. The three energy sources of the arena are Electricity (E), Gas (G), and Diesel-fuel (D). AHU stand for Air Handling Unit

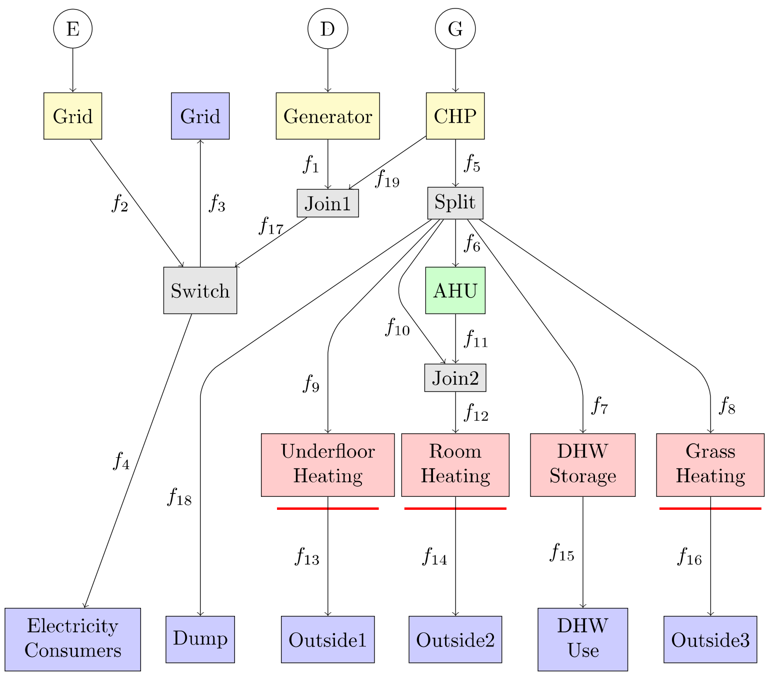

Figure 5: Commerzbank arena System model for CHP operation optimization.

6.3. Predictive model-based concept for zone control

A model-based control strategy (Mahdavi 1997, 2001b, 2008) is considered as implementation concept for an intelligent facade zone controller. In this model-based control approach, control decisions are made upon evaluation of the computed implications of virtually enacted control options. This implies that at each control decision making instance, available control options (i.e., the alternative set points or actuator positions) are virtually realized by at the zone level. The model results (projected values of the control parameter for a specific point of time in future) are then compared to identify the most promising option. A generic simplified room model for predictive zone control was developed for a test room of the UCC Environmental Research Institute building. This model is illustrated in Figure 6.

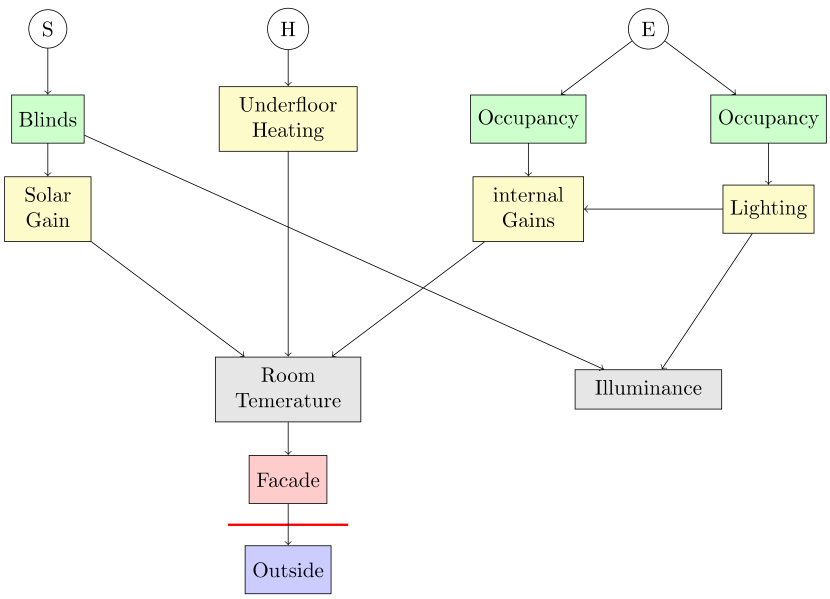

Figure 6: UCC ERI Building general room model for predictive zone control.

The model captures the main energy flows caused by solar radiation (S) and heating (H) as well as internal gains caused by occupants and electrical equipment (E) together with status variables such as air temperature and Illuminance. This model will be integrated in the proposed online optimization and adapts the related set points in the existing control.

The overall control objective is the optimized zone control based on predicted performances in terms of comfort and energy usage. A weighted sum of specific performance indicators, related to the different domains (thermal and visual aspects, air quality) will be used for the optimization.

7. Outlook

The project has thus far not only generated a basic conceptual and methodological foundation for monitoring-based energy efficiency improvement approaches in buildings, but has also led to the formulation of a number of concrete procedures and schemes for the realization of such approaches. Some of these schemes are projected to be implemented in the demonstrator facilities in the near future. Other measures shall be virtually realized to estimate their potential effectiveness. Comparison of the performance of the facilities before and after the real and virtual implementation of monitoring-aided control improvement measures is expected to provide useful data for the evaluation of the initial hypothesis. Moreover, generic features of the approach and results are to be documented for the benefit of the relevant professional community involved in the building delivery and operation process.

Acknowledgments:

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Predicting System Performance with Uncertainty

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Abstract:
The main purpose of this research is to include uncertainty that lies in modeling process and that arises from input values when predicting system performance, and to incorporate uncertainty related to system controls in a computationally inexpensive way. We propose using Gaussian Processes for system performance predictions and explain the types of uncertainties included. As an example, we use a Gaussian Process to predict chilled water use and compare the results with Neural Network. As an initial step of our research, we examine how variation in AHU supply air temperature affects chilled water use in summer time. We briefly discuss the advantages of our proposed method and future research topics in the concluding remarks.

Keywords:
Gaussian Process, Performance prediction, System controls, Uncertainty

1. Introduction

Performing better risk and uncertainty analyses of performance predictions through the entire life cycle of a building is one of the most important challenges that engineering design faces (Augenbroe, 2002). Uncertainty and sensitivity analysis have been extensively applied in science and engineering. However, their applications to building systems are still limited.

Uncertainty can enter a model when making predictions in various contexts. One way to categorize is to consider uncertainty as that lies in modeling process and that arises from input values for predictions. Uncertainty in modeling process is seldom quantified. Most uncertainty studies focus on uncertainty in input values for predictions. The input values associated with predictions can come from estimations or measurements corrupted with noise. Therefore, it is more reasonable to assign probability distributions over their domains of plausible values than to assign fixed single-point values. In some cases, it is desired to investigate the impact of variation in inputs on outputs by allowing inputs to vary in their domains.

Monte Carlo experiment is the most widely used method of analyzing input uncertainty (Hamby, 1995). Several studies used Monte Carlo method with building simulation to study building and system design with input uncertainty (de Wit & Augenbroe, 2002; Domínguez-Muñoz et al., 2010). We found two areas where there could be improvement in current uncertainty research.

Most building simulation models are highly complex and computationally expensive. Monte Carlo experiment requires a large number of model evaluations. As the complexity of uncertainty increases, the number of simulations required increases significantly. The time cost limits the extension of uncertainty analysis.

Current studies have not covered uncertainty related to system controls in operations. Measurements in system operations are usually corrupted by sensor noise. For example, measurements of temperature, humidity, air flow and water flow. Furthermore, few systems perform as intended. Usually there is a discrepancy between intended and actual performance. A straightforward example is that there exists deviation between set-points and measured values of controlled variables such as AHU supply air temperature.

The main purpose of this research is to include uncertainty that lies in modeling process and that arises from input values when predicting system performance, and to incorporate uncertainty related to system controls in a computationally inexpensive way. In the following sections of the paper, we propose using an instance-based learning method Gaussian Process for system performance predictions. We explain the types of uncertainties included in Gaussian Processes. In order to evaluate the predicting accuracy, we test a Gaussian Process with real metered data and compared its results with another widely used machine learning method Neural Network. As an initial step of applying Gaussian Process to uncertainty analysis of system operations, we present a case study of predicting energy use with uncertain AHU supply air temperature. As a conclusion, we briefly discuss the advantages of our proposed method and future research topics.

2. Methodology

The use of Gaussian Process has grown significantly after the works of (Neal, 1995 & Rasmussen, 1996) in machine learning community. Gaussian Process regression has been successfully applied to various predicting tasks. Figure 1 summarizes the procedures of using Gaussian Processes for predictions. A Gaussian Process is built upon training data, which can be sensor or metered data of a real system, or simulated data generated from complex models. Then the model takes new inputs and makes predictions with uncertainty.

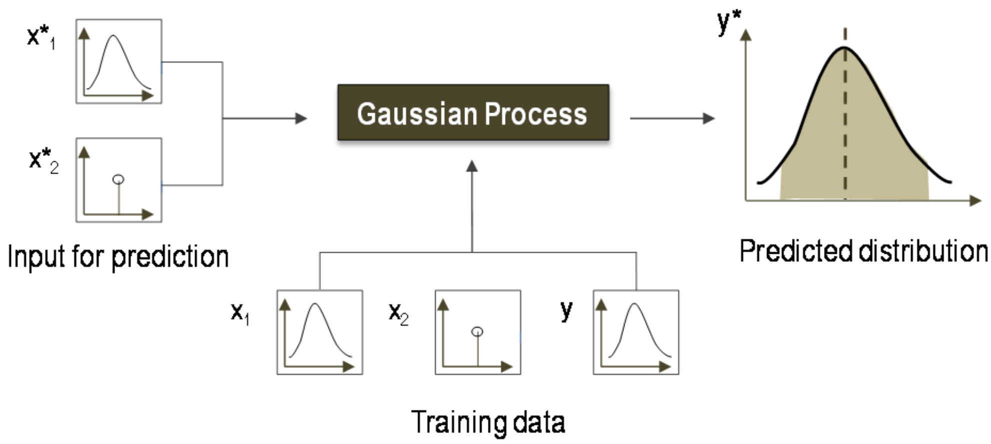


Figure 1 Diagram of predicting with uncertainty using Gaussian Process

In Gaussian Processes, the uncertainty in modeling process comes from noises in training data and distance between training inputs and inputs associated with predictions. One source of noises in training data is measurement noise. For example, it is reasonable to assume that time is noise-free, while the measurement of flow rate is usually corrupted by sensor noise. Measurement noise may exist in both training inputs and training targets. While for noise in training targets, there is another source of uncertainty. The features in an existing model might not fully explain the variance in training targets. There might be some other important features that affect outputs. Noise in targets might be reduced if we could recognize some more features and include them in the model. The variance of a prediction also depends on the distance between its input point and training inputs. Gaussian Process is an instance-based learning method. If a new input point is far from training points, the variance is large in the prediction.

Variation in input values associated with predictions leads to an extra uncertainty in predictions. In some cases, it is our interest to investigate the impact of inputs on the output by varying inputs according to appropriate distributions and examining the corresponding distributions of outputs.

We briefly list the formulas of Gaussian Process regression we use in this study. For a comprehensive introduction to Gaussian Process modeling, please refer to (Rasmussen & Williams, 2006). The following formulas do not include the noise in training inputs. In this study, training inputs are assumed to be noise-free. In our further research, we will include noise in training inputs.

When using Gaussian Process for regression, for a noise-free input $\mathbf{x}^*$, the predictive distribution is Gaussian with mean $\mu(\mathbf{x}^*)$ and variance $\sigma^2(\mathbf{x}^*)$ (Rasmussen & Williams, 2006)

$$\mu(\mathbf{x}^*) = \mathbf{k}(\mathbf{X}, \mathbf{x}^*)^{\mathrm{T}}(\mathbf{K} + \sigma_n^2\mathbf{I})^{-1}\mathbf{y} \tag{1}$$

$$\sigma^2(\mathbf{x}^*) = k(\mathbf{x}^*, \mathbf{x}^*) - \mathbf{k}(\mathbf{X}, \mathbf{x}^*)^{\mathrm{T}}(\mathbf{K} + \sigma_n^2\mathbf{I})^{-1}\,\mathbf{k}(\mathbf{X}, \mathbf{x}^*) \tag{2}$$

where the choice of covariance function in this study is

$$k(\mathbf{x}_i, \mathbf{x}_j) = \sigma_f^2 \exp\left[-\frac{1}{2}\left(\mathbf{x}_i - \mathbf{x}_j\right)^T \mathbf{W}^{-1}\left(\mathbf{x}_i - \mathbf{x}_j\right)\right]$$

and

$$\mathbf{W} = \mathrm{diag}[w_1^2, w_2^2, \dots, w_D^2]$$

$\mathbf{k}(\mathbf{X}, \mathbf{x}^*)$ is the $N \times 1$ vector of covariance functions between training inputs $\mathbf{X}$ and the new input. $\mathbf{K}$ is the $N \times N$ matrix of covariance functions between each pair of training inputs. σ_n^2 denotes the variance of Gaussian noise in training targets $\mathbf{y}$. σ_f, σ_n and $w_1, w_2 \dots w_D$ are hyperparamters to be trained in a Gaussian Process.

Covariance function is the central part of Gaussian Process modeling. Inputs that are judged to be close by the covariance function are likely to have similar outputs. A prediction is made by considering the covariances between the predictive case and all the training cases (Rasmussen, 1996).

To incorporate uncertain values of an input point associated with a prediction, assuming the input distribution is Gaussian $\mathbf{x}^*\sim\boldsymbol{\mathcal{N}}_{\mathbf{x}^*}(\boldsymbol{\mu}_{\mathbf{x}^*},\boldsymbol{\Sigma}_{\mathbf{x}^*})$, then the predictive mean $\mu(\boldsymbol{\mu}_{\mathbf{x}^*},\boldsymbol{\Sigma}_{\mathbf{x}^*})$ and variance $\sigma^2(\boldsymbol{\mu}_{\mathbf{x}^*},\boldsymbol{\Sigma}_{\mathbf{x}^*})$ with the noisy input are (Girard et al., 2003)

$$\mu(\boldsymbol{\mu}_{\mathbf{x}^*},\boldsymbol{\Sigma}_{\mathbf{x}^*}) = \mathbf{q}^{\mathrm{T}}\boldsymbol{\beta} \tag{3}$$

$$\sigma^2(\boldsymbol{\mu}_{\mathbf{x}^*},\boldsymbol{\Sigma}_{\mathbf{x}^*}) = k(\boldsymbol{\mu}_{\mathbf{x}^*},\boldsymbol{\mu}_{\mathbf{x}^*}) + \mathrm{Tr}[(\boldsymbol{\beta}\boldsymbol{\beta}^{\mathrm{T}} - (\mathbf{K}+\sigma_n^2\mathbf{I})^{-1}\mathbf{Q})] - (\mathbf{q}^{\mathrm{T}}\boldsymbol{\beta})^2 \tag{4}$$

where

$$\boldsymbol{\beta} = (\mathbf{K}+\sigma_n^2\mathbf{I})^{-1}\mathbf{y}$$

$$q_i = |\mathbf{W}^{-1}\boldsymbol{\Sigma}_{\mathbf{x}^*}+\mathbf{I}|^{-\frac{1}{2}}\sigma_f^2 \exp\left(-\frac{1}{2}(\boldsymbol{\mu}_{\mathbf{x}^*}-\mathbf{x}_i)^{\mathrm{T}}(\boldsymbol{\Sigma}_{\mathbf{x}^*}+\mathbf{W})^{-1}(\boldsymbol{\mu}_{\mathbf{x}^*}-\mathbf{x}_i)\right)$$

and

$$Q_{ij} = |2\mathbf{W}^{-1}\boldsymbol{\Sigma}_{\mathbf{x}^*}+\mathbf{I}|^{-\frac{1}{2}}\sigma_f^2\exp\left(-\frac{1}{2}\left(\frac{\mathbf{x}_i+\mathbf{x}_j}{2}-\boldsymbol{\mu}_{\mathbf{x}^*}\right)^{\mathrm{T}}\left(\boldsymbol{\Sigma}_{\mathbf{x}^*}+\frac{1}{2}\mathbf{W}\right)^{-1}\left(\frac{\mathbf{x}_i+\mathbf{x}_j}{2}-\boldsymbol{\mu}_{\mathbf{x}^*}\right)\right)\cdot$$
$$\sigma_f^2\exp\left(-\frac{1}{2}(\mathbf{x}_i-\mathbf{x}_j)^{\mathrm{T}}(2\mathbf{W})^{-1}(\mathbf{x}_i-\mathbf{x}_j)\right)$$

With the assumption of Gaussian input distribution and using the covariance function above, there is no need to run extra simulations to incorporate uncertain values of an input point. It can be simply derived from the analytical expressions above. This significantly reduces the time cost of uncertainty analysis.

3. Case Study

3.1. Predict Chilled Water Use

In this case study, we test Gaussian Process modeling on metered chilled water use data. Data samples are on an hourly basis. The target is chilled water (W/m^2). The features include outside air dry-bulb temperature (°C), humidity ratio (kg/kg), the hour of the day. We use $\sin\left(\frac{2\pi\cdot\text{hour}}{24}\right)$ and $\cos\left(\frac{2\pi\cdot\text{hour}}{24}\right)$ to represent the hour of the day. It is assumed that measurements of time, temperature and humidity ratio are noise-free, while measurements of chilled water use are noisy.

Figure 2 shows the 24-hour prediction of chilled water use by a Gaussian Process trained by 216 hourly data points. The solid line indicates the predictive mean, grey area as 95% confidence region, compared with observed values shown in red dots. Most of the predictive means are close to observed values. Noises in training targets and the distance between training inputs and test inputs account for the uncertainty in predictions.

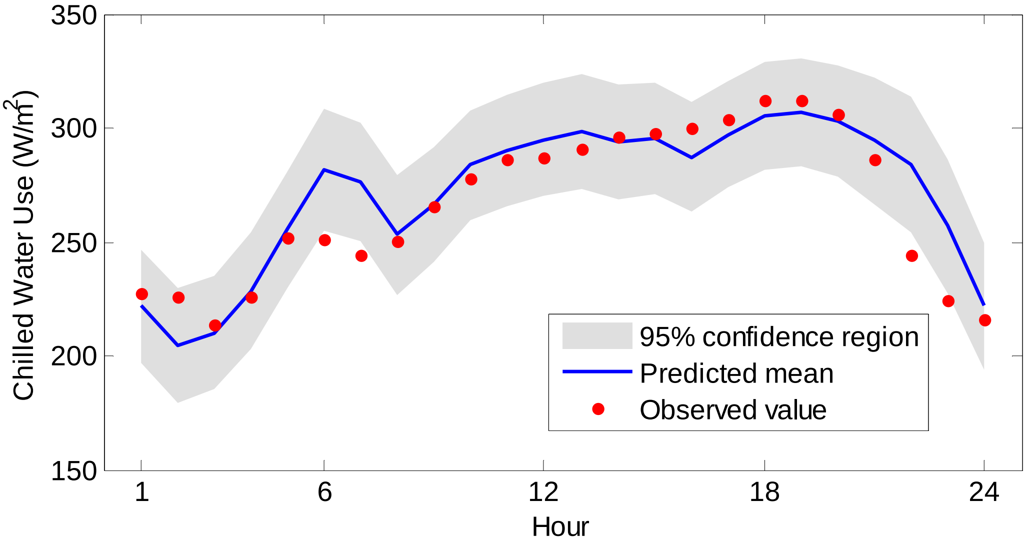


Figure 2 24-hour prediction of chilled water use

In order to evaluate the accuracy of Gaussian Process, the results are compared with those of Neural Network using the same inputs. Neural Network has been used to predict building energy use approximately since the 1990s. The reported error rates of short-term prediction (1h to 24h) can be as low as 1%-5%. Long-term prediction accuracies are also promising (Dodier & Henze, 2004). In this study, the training of neural network is implemented through Matlab (version R2011a) Neural Network Toolbox. In this model, there is one hidden layer with 15 neurons. The activation equation in the hidden layer is sigmoid, and linear in the output layer. The training algorithm is Levenberg-Marquardt backpropagation.

The coefficient of determination is used to compare how well the predictions are between Gaussian Process and Neural Network. The coefficient of determination R^2 is calculated as

$$R^2 = 1 - \frac{\sum_i (y_i - f_i)^2}{\sum_i (y_i - \bar{y})^2} \tag{5}$$

where the values y_i are observed values of targets, the values f_i are predicted values. For Gaussian Processes, values f_i are the predicted mean values. $\bar{y}$ is the mean value of the observed targets. The better a model is likely to predict future outcomes, the closer the value of R^2 is close to 1. A larger R^2 means a smaller sum of squared errors of prediction.

Metered chilled water use for 140 days is available for this study. Three types of prediction tasks are experimented, which are 24-hour prediction, 72-hour prediction and 9-day prediction. 10-fold cross-validation is used in model training and testing. The overall R^2 value is used for comparison. The results are shown in Figure 3. In this comparison study, it turns out which model predicts better depends on the time scale of prediction and characteristics of data.

Gaussian Process seems to outperform Neural Network on short-term prediction. According to Figure 3, Gaussian Process shows a better performance than Neural Network when predicting chilled water use 24-hour ahead. However, among the 14 cross-validations of 24-hour prediction, Gaussian Process does not outperform Neural Network all the time. When using data groups shown in

(a) GP better (b) NN better (c) GP better

Figure 4(a) and (c), the R^2 values of Gaussian Process are higher, while using data groups shown in

(a) GP better (b) NN better (c) GP better

Figure 4(b), the R^2 values of Neural Network are higher. It appears that Gaussian Processes lose advantages when chilled water use has a strong linear relationship with outside air temperature. Two modeling methods perform almost same for 72-hour prediction. The R^2 value of Neural Network is slightly higher regarding 9-day prediction.

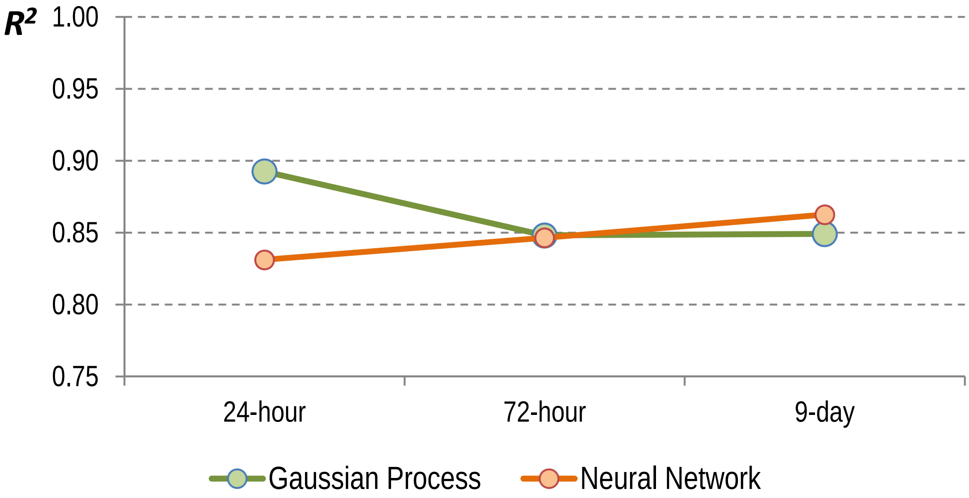
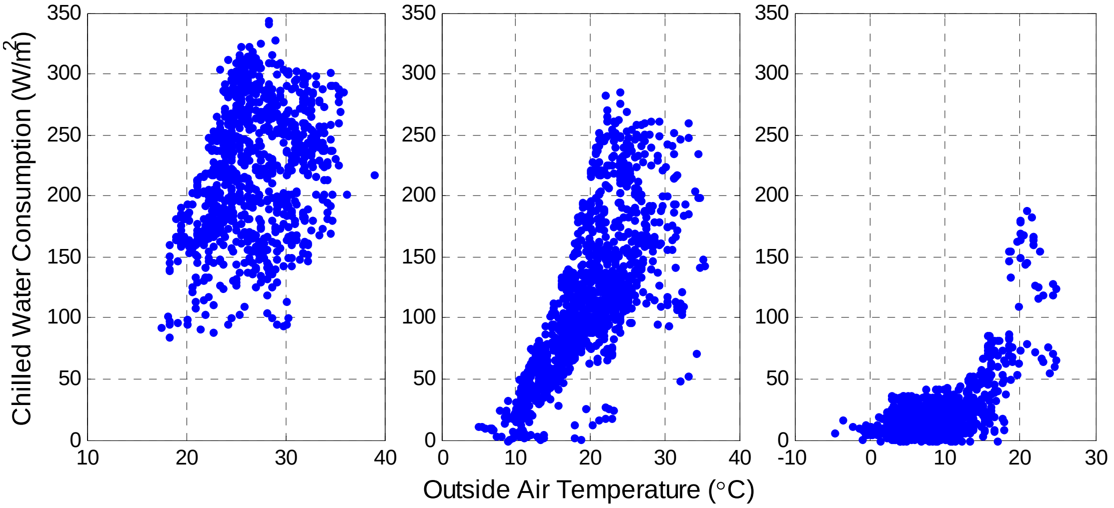


Figure 3 Comparison of $\boldsymbol{R^2}$ values of Gaussian Processes and Neural Networks



(a) GP better (b) NN better (c) GP better

Figure 4 Data groups on which Gaussian Processes and Neural Networks have different predictive accuracy

It can be concluded from the cross-validations above that the predictive accuracy of Gaussian Processes is close to the widely used Neural Networks. In some cases, such as several short term prediction tasks, Gaussian Processes even show some advantages. More careful design for comparative studies might be necessary in order to be confident that the observed R^2 of these two methods reflects their real accuracy in performance rather than a random fluctuation. Furthermore, it is unreasonable to generalize the conclusion of this experiment, which is based on a particular dataset, to other datasets. However, this experiment still enables us to get an idea of how well Gaussian Processes will perform on other datasets with similar characteristics, which seems very promising.

3.2. Examine the Impact of AHU Supply Air Temperature on Chilled Water Use

In this case study, we examine the impact of variation in AHU supply air temperature on chilled water use. The system under study is an AHU VAV system with terminal reheat for an office building, which runs 24 hours a day. One summer month of measured hourly AHU supply air temperature is available for study. Its histogram is shown in Figure 5.

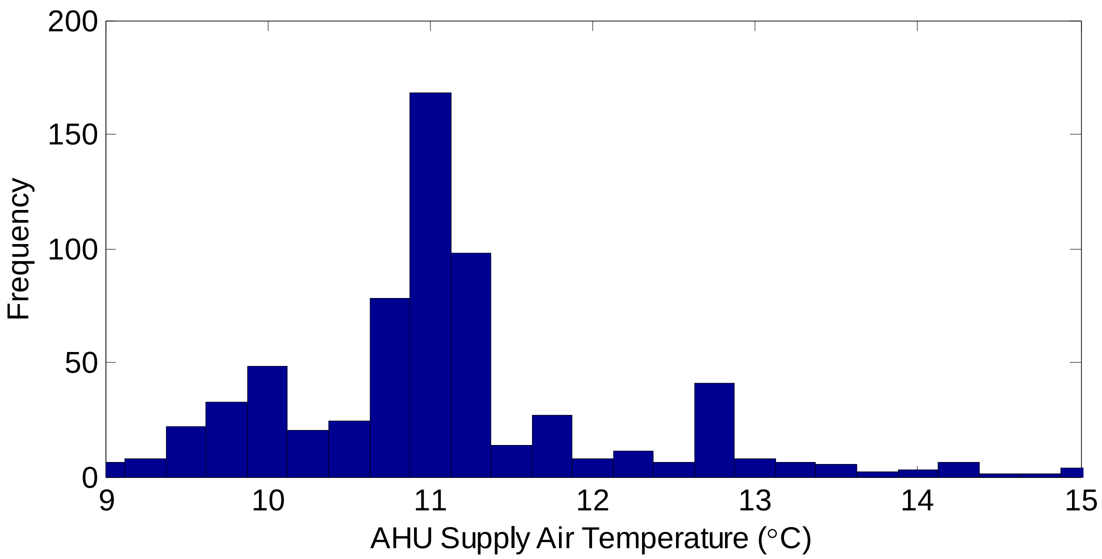


Figure 5 Histogram of measured AHU supply air temperature

The set-point of AHU supply air temperature is 11.1°C. The mean value of measured hourly AHU supply air temperature equals the set-point. However, a standard deviation of 1.1°C is observed. The AHU supply air temperature varies from 9°C to 15°C. Poor PID control, insufficient or excessive supply of chilled water might account for the deviation from set-point.

The wide range of variation in actual AHU supply air temperature directly affects system energy use. One conventional way to examine the extent of the impact is to perform a Monte Carlo experiment, generating random AHU supply air temperature from its probability distribution and running simulations over all combinations of the inputs. We propose a different method, using a Gaussian Process to build a surrogate model based on data points available and plugging the input distribution into equations (3) and (4) to get the predictive distribution of energy use directly.

Some constraints exist when deriving the predictive distribution of output from analytical expressions of equations (3) and (4). First, the distributions of the inputs to be examined are assumed to be Gaussian. For other distributions, approximate or exact analytical expressions are also possible, but will be different. Second, training sets need to cover most of the input domain to be examined in the study. Otherwise, prediction accuracy will be compromised and the uncertainty introduced by modeling process will be dominant. Third, the predictive distribution includes the uncertainty of modeling process. Comparison with the predictive distribution derived from noise-free inputs is necessary. Lastly, the computational cost of Gaussian Process is $O(n^3)$, where n is the number of training points. If the number of training points needed for the model is large, the advantage of using Gaussian Processes is less prominent.

We build a Gaussian Process using time, outside temperature and humidity, and AHU supply air temperature as training inputs, chilled water use as training targets. The data is on an hourly basis for nearly one month. The training inputs are treated as noise-free, while training targets as noisy. The training R^2 is 0.9808. Then for each point, we use $\boldsymbol{\mathcal{N}}(11.1, 1.1^2)$ as the new AHU supply air temperature distribution. The new predictive distributions of hourly chilled water use are calculated according to equations (3) and (4). An extra uncertainty in predictions is introduced by variance in AHU supply air temperatures.

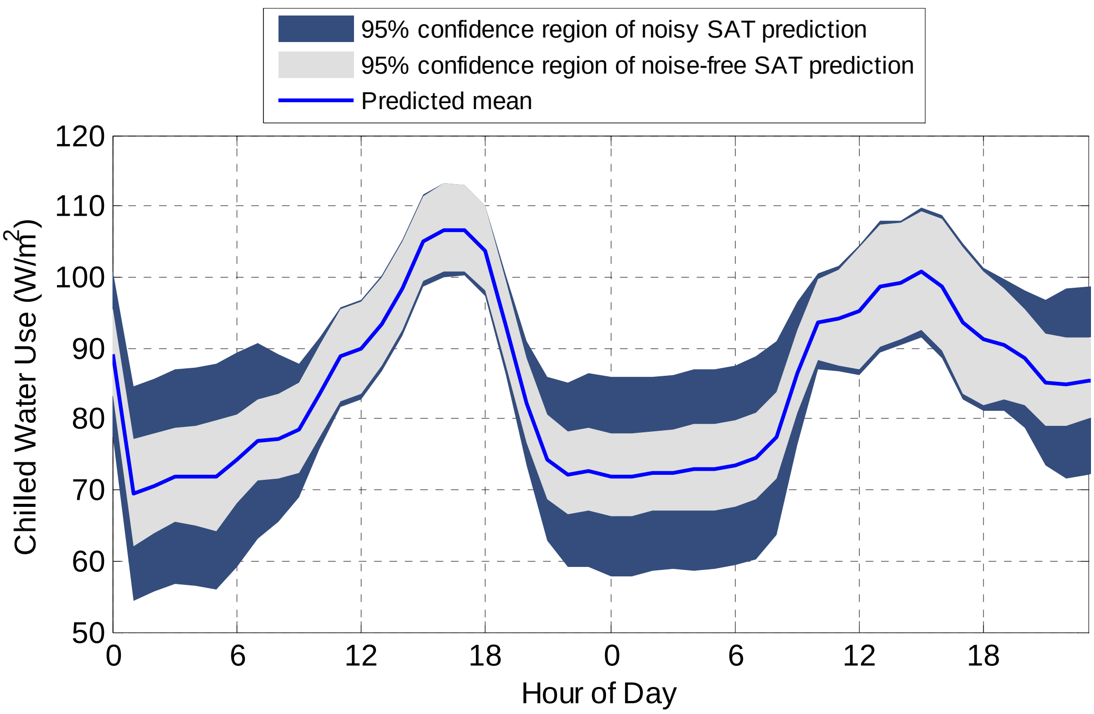


Figure 6 Predictive distributions of hourly chilled water use which include the uncertainty introduced by the variance in AHU supply air temperatures

Figure 6 shows the predictive distributions of chilled water use for 48 hours. The results are compared with the predictive distributions derived from noise-free AHU supply air temperature, which is assumed to be 11.1°C all the time. With a variance of 1.1^2 in AHU supply air temperature, the predictive means stay almost same, while the 95% confidence regions expand in some time periods. The dark blue area is the extra uncertainty introduced by variance of AHU supply air temperature.

We can see from Figure 6 that, during working hours, the variation in AHU supply air temperature almost has no effect on chilled water use. In summer during working hours, the amount of chilled water needed to process the cooling load does not change with AHU supply air temperature. When cooling load is high, higher AHU supply air temperature results in larger supply air flow rate, and the chilled water needed to process the air remains the same. And vice versa. During nighttime, the outside air temperature drops and internal load is minimal. As cooling load decreases, supply air flow rate is fixed at its minimum. Therefore, increasing AHU supply air temperature reduces chilled water use. A low AHU supply air temperature will increase chilled water use, and more reheat is necessary to compensate the excessive cooling. Around 1°C standard deviation in AHU supply air temperature accounts for a standard deviation as large as 5-8% of the predictive mean values of chilled water use during some night hours.

The example above shows how to use a Gaussian Process to study the uncertainty introduced by input variation. With the assumption that the input distribution is Gaussian, the predictive distribution can be calculated directly without Monte Carlo experiment. It is necessary that the training set should cover the most of the input domain. Otherwise, the uncertainty introduced by modeling process itself would be too large. Usually this is not an issue if data is generated from simulation. It might be challenging when building a Gaussian Process based on observations from actual performance. The example above uses measured AHU supply air temperature, while the chilled water use is simulated by EnergyPlus since no metered data is available.

4. Concluding Remarks and Further Work

This paper introduces predicting system performance through Gaussian Processes, which include uncertainty that lies in modeling process and arises from input values. Instead of building a model based on physical principles and using metered data for calibration, Gaussian Processes can directly use observed system performance to build a statistical model for further analysis. It avoids configuring numerous parameters required, which are difficult to know and estimate. Gaussian Processes can also serve as surrogate models for computationally expensive simulations. The outputs are predictive distributions with mean and variance. With the assumption that the input distribution is Gaussian, the uncertainty introduced by input variation can be calculated directly without Monte Carlo experiments.

In the first case study, we use a Gaussian Process to predict chilled water use based on time information, outside temperature and humidity. In the second case study, we examine how the variation in AHU supply air temperature affects chilled water use in summer time. As an initial step of our research, we still rely on simulated data to explore the application of Gaussian Processes, in order to develop and validate the methodology. In the future work, it will be valuable to apply Gaussian Processes to measured data of actual system performance. In addition to AHU supply air temperature, it will be interesting to study the uncertainty introduced by non-ideal control of air mixing in AHU, air flow rate and reheat in VAV terminal units, and their effect on electricity, heating and cooling energy use. Most important, we want to explore how to utilize the information of uncertainty provided by Gaussian Processes in addition to sensitivity analysis. One promising application that comes to our mind is fault detection and diagnosis, especially when our focus is on the uncertainty introduced by non-ideal control. Since Gaussian Process not only gives the predicted values, but also a measure of how confident about predictions, this extra information could probably help increase credibility in fault detection and diagnosis, especially to reduce false alarm occurrences. This will be our potential research topic in the future.

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Energy Star for Hospitals 2011 Update: Progression or Regression?

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Abstract:
The Energy Star performance rating system for buildings has achieved widespread adoption in the building sector as a standard benchmark for energy performance. In 2011, the U.S. EPA released an updated technical methodology for its Energy Star performance rating system for hospitals, shifting how the score is calculated. The new rating system, similar to the previous rating system, is still a poor metric for benchmarking hospitals and should be used with caution. The aim of this paper is to critique the methodology used in the Energy Star for Hospitals 2011 Update. The paper reviews the changes between the 2001 methodology and 2011 methodology, how Energy Star views usage of different fuel types in its score, and lastly items that did not change in the 2011 hospital methodology update which are still causing confusion amongst Energy Star users and are causing significant error in the Energy Star score calculations.
Keywords:
benchmark, Energy Star, hospital, performance.

1. Introduction

Benchmarks are crucial tools in our society. The term "benchmark" or sometimes "bench mark" has various origins, some of which are related to surveying and some related to cobblers but, no matter its origin, the word is closely connected to the idea of measurement. A measurement is made and all subsequent measurements are compared to the original measurement, or benchmark. Sometimes that measurement is used as a static standard or reference point ad infinitum, but in many cases the benchmark becomes a moving standard which changes over time. When the benchmark is performance related, as performance improves so also must the benchmark improve to be of continued accuracy. The four-minute mile was a good benchmark in 1954 when it was broken by Roger Bannister, but is wholly inadequate to measure the best runners today, who typically run the mile in under three minutes and forty-five seconds.

In the realm of buildings, benchmarks, particularly energy benchmarks, are a relatively new phenomenon. Until the 1970's, energy in developed countries was widely available and inexpensive, thus there was no great push for buildings to perform with any level of energy efficiency. Indeed, energy efficiency was an alien notion for buildings because there was no real idea, no benchmark whatsoever, of what an energy efficient building looked like to begin with. When there is no benchmark, there is no ability to see how an object, be it a runner or a building, is performing. But the world changed - energy is no longer inexpensive, and buildings are more energy-intensive now than ever before. But a void existed, and the ability to determine if a building was energy efficient or not was non-existent.

Seeking to fill the void in the United States, in 1999 the U.S. Environmental Protection Agency created Energy Star for Buildings, as well as Portfolio Manager, an online benchmarking tool which allowed users to input their utility bills while simultaneously tracking important energy performance metrics for their building, such as the Energy Utilization Intensity (E.U.I.) and Energy Cost Intensity (E.C.I.). Since its inception, Portfolio Manager has also added the ability to track water consumption, as well as greenhouse gas emissions. As of September of 2011, the U.S. EPA reported that over 250,000 buildings had been benchmarked in Portfolio Manager.

The most prominent part of Energy Star Portfolio Manager came with the advent of the Energy Star performance rating system, more colloquially known as the Energy Star score. The Energy Star score has become the golden standard for energy performance; the U.S. Green Building Council, the Green Building Initiative as part of Green Globes, and others have adopted the Energy Star score as part of their rating systems. However, not all building types are eligible for an Energy Star score; presently only fifteen different building types are eligible to be rated for an Energy Star score, as shown in Table 1.

Table 1: Building types eligible for the Energy Star score.

Building Type	Minimum Gross Square Footage (ft^2)
Bank/Financial Institution	≥ 1,000
Courthouse	≥ 5,000
Data Center	N/A
Hospital (General Medical and Surgical)	≥ 20,000
Hotel	≥ 5,000
House of Worship	≥ 1,000
K-12 School	≥ 5,000
Medical Office	≥ 5,000
Municipal Wastewater Treatment Plant	N/A
Office	≥ 5,000
Residence Hall/Dormitory	≥ 5,000
Retail Store	≥ 5,000
Senior Care Facility	≥ 5,000
Supermarket	≥ 5,000
Warehouse	≥ 5,000

The Energy Star score is a 1-100 number generated in Portfolio Manager after eligibility requirements for the respective building have been met (more on that later), specific data related to the building type (e.g. square-footage) have been entered, and a finite amount of utility months (varies dependent upon building type) have been entered into the Portfolio Manager system. The score is meant to benchmark the building, providing an energy efficiency score for the building amongst its peers in a respective building type. A score of 75, for example, is meant to indicate that the building scores amongst the 75^{th} percentile in energy efficiency, and that only 25% of the building population is more energy efficient.

The technical methodology used to generate the score is different for every building type (thus, the grading criteria for a Senior Care Facility is not the same as a Warehouse, thankfully), but each methodology operates in the same manner with three important parts: Dependent Variables, Independent Variables, and Reference Data Set. A description of how the Energy Star score is calculated is shown in Figure 1.

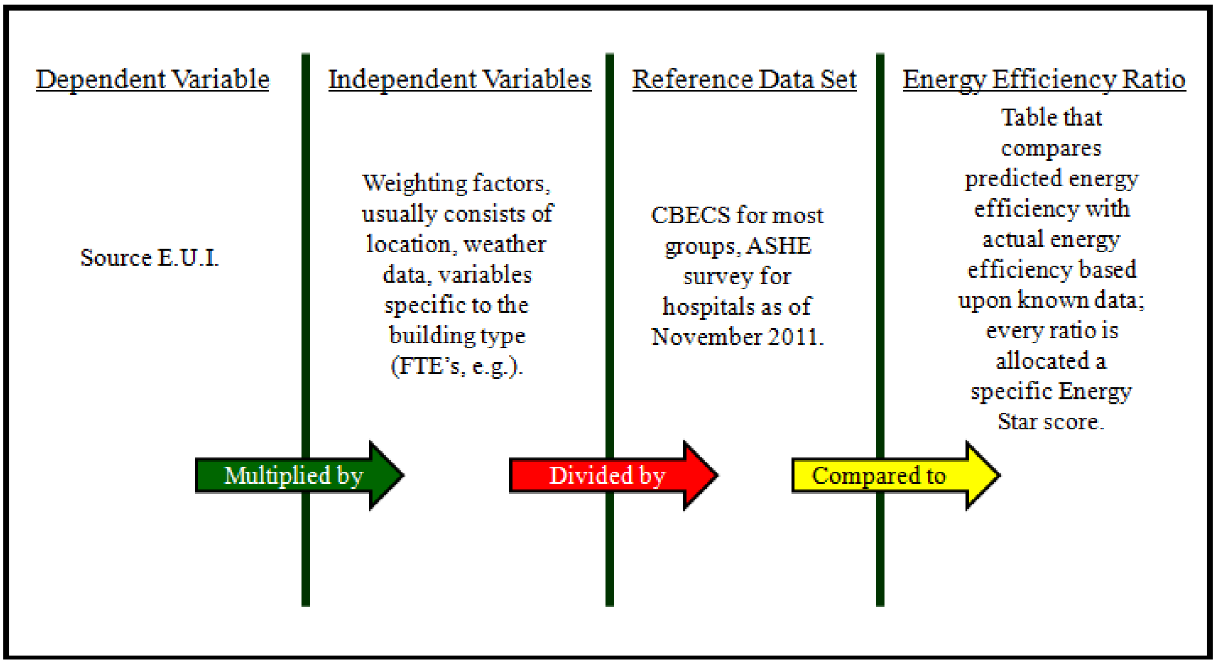

Figure 1: General methodology for calculating the Energy Star score.

More will be discussed on this methodology in later sections, but it should be noted that Energy Star uses Source E.U.I., not Site E.U.I., as its dependent variable. Thus, a multiplying factor is given for each specific fuel type (electricity, natural gas, coal) to create energy equivalence, instead of using the site E.U.I. which does not factor out losses based on transportation or other means. Although losses due to transportation or the grid vary significantly from one utility company to the next, Energy Star does not punish or promote buildings based upon their utility provider, but instead uses a common multiplier for each type of utility, regardless of the provider.

2. Energy Star for Hospitals

The first Energy Star Performance Rating system for Hospitals was released in November of 2001; the scoring system was tweaked slightly in 2007, but otherwise remained the same for the next decade. The second version for Hospitals was released in November of 2011. Since its inception, according to Clark Reed of the EPA, as of December of 2011 over 3600 hospitals had been benchmarked in Portfolio Manager – an astounding 69% of the 5200 community and Department of Defense Hospitals in the United States. A comparison between the two methodologies is shown in Table 2.

Table 2: Overview of Energy Star for Hospitals.

	2001	2011
Reference Data	1997 EPRI Survey	2010 ASHE Survey
Qualifications	3	4
Dependent Variable	Natural Log of Source E.U.I.	Source E.U.I.
Independent Variables	8	4

2.1 Reference Dataset

The most important change between the 2001 methodology and the 2011 methodology is the reference data used to compare all buildings to. The Energy Star score is not based on data entered into Portfolio Manager (which would cause the score to constantly fluctuate based upon the buildings entered), but rather is based on a fixed set of data that does not change with time. The original data was based on a 1995 Electric Power Research Institute Survey; the survey included records for Acute Care/Children's Hospitals (415 records), Cancer Centers/Clinics (4 records), Skilled Nursing Facilities (45 records), Psychiatric Hospitals (10 records), and Rehabilitation Centers (19 records), for a total of 493 records to compare to.

However, by 2010 the survey was already severely outdated, particularly considering the increasing energy intensity rise in hospitals due to electrical equipment. The 2011 methodology uses an American Society for Healthcare Engineering (ASHE) survey from 2010. Although the survey is newer, the sample size is only 39% of the previous methodology as there are only 191 hospitals in the dataset. Post-processing was also done on the data to address biases in the data, such as an over-representation of hospitals in a specific geographic location or by hospital ownership. Statistics from the ASHE survey are shown in Table 3.

Table 3: 2011 Reference Dataset.

Characteristic	ASHE Survey Sample
Sample Size	191
Average Source E.U.I.	485
Average Square Footage	448,061
Average Staffed Beds	197
Average MRI Machines	1
Average FTE Workers	1167

2.2 Qualifications

The qualifications to be considered to receive an Energy Star for Hospitals score were slightly tweaked between the 2001 methodology and the 2011 methodology. The four qualifications for the 2011 methodology are as follows:

1. More than 50% of the gross floor area of all buildings must be used for general medical and surgical services.
2. More than 50% of the licensed beds must provide acute care services.
3. Long-term care hospitals that are certified as acute care hospitals are not eligible because they provide patients with acute care for extended inpatient stays, defined by federal statute as an average of 25 days or more.
4. Ambulatory surgical centers, specialty hospitals, and other types of long-term care facilities should benchmark under the "Other" space type category.

2.3 Dependent Variable

The dependent variable for both the 2001 methodology and the 2011 methodology is still the

Source E.U.I.; however it is no longer calculated in natural log form.

2.4 Independent Variables

Apart from the reference data set, the second biggest change in the 2011 methodology is the selection of the independent variables. A comparison of the two methodologies is shown in Table 4.

Table 4: Independent Variables

2001	2011
Natural log of gross square footage	Number of FTE workers per 1000 square foot
Acute Care/Children's Hospital	Number of staffed beds per 1000 square foot
Tertiary Care	Number of MRI machines per 1000 square foot
Natural log of number of beds	Cooling degree days
Natural log of the maximum number of floors	
Above ground parking facility	
Heating degree days	
Cooling degree days	

As shown, the independent variables have changed drastically. The 2001 independent variables included three (acute care/children's hospital, tertiary care, above ground parking facility) that were simple yes/no questions; none of these exist in the 2011 methodology. The 2001 methodology also included gross square footage, whereas gross square footage as a standalone variable has been dismissed completely in the 2011 methodology. The 2001 methodology focused on the number of beds total for the hospital, whereas the 2011 dismisses the total number of beds and is only focused on "staffed" beds per 1000 square foot. The number of floors is also no longer used in the 2011 calculation. The biggest deletion from the 2011 methodology though is the complete removal of heating degree days, and cooling degree days are the only instrument of weather considered in the calculation.

The 2011 methodology adds several variables that were not considered in the 2001 methodology, namely the number of full-time equivalent (FTE) workers, the number of staffed beds, and the number of MRI machines in the facility, all averaged out per 1000 square foot. It is interesting to note that gross square footage as a separate variable is not considered, only when it is melded with another variable.

3. Critique

The value of any benchmark correlates directly with its ability for any user to make accurate judgments with its usage. Like a ruler, it must be able to be used quickly to determine if something is four inches in length; if we cannot make this determination, or if the benchmark is difficult to use, the benchmark is of little value. Extra burden lies on performance-based benchmarks (like the example of the four minute mile earlier), because these benchmarks must be updated over time. Thus, the Energy Star for Hospitals performance-rating system has an admittedly very difficult task – the ability to accurately gauge how energy efficient a hospital is compared to its peers. There are four primary categories where I believe the Energy Star for Hospitals 2011 methodology falls short of being a good benchmark: the reference dataset, the independent variables used, the usage of source E.U.I. rather than site

E.U.I., and the guidelines classification for hospitals. I will discuss each of these critiques in the sections below.

3.1 Poor reference dataset quality

The goal of any reference dataset is to use a small amount of data to be indicative of a larger section as a whole. The 2001 methodology reference dataset used a survey that included 493 hospitals, nearly ten percent of the amount of hospitals in the United States. The survey was also available and viewable by the general population and approved to be a good overall representation of acute care hospitals. The 2011 methodology reference dataset on the other hand only uses 191 hospitals, accountable for only 3.7% of hospitals in the United States. The dataset is also currently unavailable to independent third parties for review of the accuracy and completeness of the data, whereas as other data (such as CBECS) is openly available. The EPA has also confessed in its technical methodology for the 2011 methodology that it has biased the data in some fashion, but it does not release the data from the survey nor indicate how the survey has been mathematically biased. All of these points make building confidence in the reference dataset difficult.

3.2 Independent variable selection

The independent variables (weighting factors) for the 2011 methodology were selected by mathematical regression techniques of the reference dataset. These variables were chosen because they showed a direct correlation between their characteristic and energy intensity of the building. However, strange independent variables were chosen as showing correlation with energy intensity, while other variables, which would seem to be obvious selections for independent variables were not chosen.

Ultimately, the efficiency of the hospital is rated according to its energy density, measured in energy used per year per square foot of the building. Thus, energy density is important. It is understandable how MRI machines were selected as an independent variable; MRI machines are electricity intensive machines which usually have their own data rack, require intense cooling, and have tight temperature and humidity requirements. However, other electrical intensive machines, such as PET Scan and CT Scan, were not chosen. Also, the most energy intensive areas of a hospital, operating rooms (which require extraordinarily rigorous temperature and humidity requirements, and use lots of steam-cleaning equipment such as sterilizers and washers), kitchens (which are heavily energy intensive with cooking equipment and fume hoods), gyms or swimming pools, and laundry facilities (which use high-pressure steam for extended periods of time) were not considered – very head-scratching for measuring energy density in buildings.

Inversely, areas that have low density were not necessarily counter-weighted. Some hospitals, due to their unique layout, have a high percentage of medical office space as part of their building or campus. Medical office space is a low density energy space compared to inpatient care areas, and would greatly affect the E.U.I. of any facility.

3.3 Source E.U.I.

One of the interesting things about the Energy Star performance rating system, for hospitals as well as other types of buildings, is its usage of source E.U.I. rather than site E.U.I. as the dependent variable. The reason source E.U.I. is used is the idea of energy equivalence, so as to not punish buildings dependent upon their fuel-type (with the hoped-for ambition of being able compare buildings that use a large amount of natural gas with buildings that use a small amount of natural gas or buildings which are all-electric). However, in spite of its intention, the usage of source E.U.I. appears to in fact punish buildings that use more natural gas than electricity. It does this by using metrics related to electricity rather than natural gas as the independent variables, due to the multiplying factor given to electricity when changing it from site E.U.I. to source E.U.I. As shown above, cooling degree days and MRI machines were selected as independent variables because they showed a high correlation with energy usage with the reference data set. However, both of these items are generally electricity-based consumers. Items that use natural gas usually do not get selected as independent variables (heating degree days was completely dropped from the 2011 methodology), which in effect plays down their significant role. In turn, buildings that have a higher blend rate of natural gas to electricity tend to score lower Energy Star scores than their all-electric or mostly electric brethren.

3.4 Classification confusion

One attribute for the Energy Star for hospitals guideline that went completely unchanged with the updated 2011 methodology is the hospital classification guideline. The guideline is meant to give Portfolio Manager users guidance on how to allocate utilities for hospitals, as well as different metering techniques (such as when a hospital has a data center, parking lot lighting, et al.). However, the classification guideline is quite short and poorly worded which causes confusion when creating using the Portfolio Manager system.

Hospitals come in a variety of shapes and sizes. Some hospitals are encapsulated in one building that is on one electric meter. Some hospitals on the other hand are built in campus-like setups where inpatient care may be in one building, surgery may be in another building, ambulatory care in another, and so on. Each of these buildings may also have drastically different blend rates of different fuel types, and may have parking lot lighting sub-metered (or not) and have data centers sub-metered (or not). However, the classification guideline does not provide clear and accurate information on how hospitals in a variety of different setups are to be entered correctly. This is the biggest deficiency in Portfolio Manager, because improper entry of utility data can greatly increase or decrease the Energy Star score by plus or minus twenty points.

4. Conclusions

Benchmarks are vital tools for our society – they play an important and necessary role to advance our understanding of a variety of characteristics. For many years there had not been a benchmark for building energy efficiency, and Energy Star has valiantly began this process. The Energy Star for hospitals 2011 methodology is a slight improvement over the 2001 methodology, but it is still an inaccurate benchmark for building energy efficiency. The selection of a smaller dataset, the continued usage of strange independent variables while disregarding other independent variables, and the continued confusion over the classification of spaces in Portfolio Manager makes it difficult to have confidence in any Energy Star for Hospitals score generated.

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Identification of changes needed in supermarket design for energy demand reduction

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Abstract:
Supermarkets use 3% of UK energy. To satisfy building regulations supermarket buildings are modeled in considerable detail. Lighting, occupancy, and small electrical energy impacts are included in this modeling. However, refrigeration energy is not, as it is classified as "process energy" rather than "building related". Refrigeration energy, which can be very significant, is therefore currently "unregulated" and as a result, heat transfers related to refrigeration cabinets are typically not incorporated in modeling of the building at design stage.

This paper explores the comparative energy demands of supermarket stores modeled, using a simple first-order dynamic model, executed on Excel, and "optimized" firstly with, and secondly without, the cooling effect of refrigeration cabinets included in the model. A recently built supermarket is modeled. Results suggest that the energy demand of a new store could be reduced by 15-25% by improvement of the building envelope design with process energy included in the modeling.

Keywords:
Building energy modeling, building regulations, refrigeration, supermarket energy

1. Introduction

In UK, supermarkets account for 3% of national electricity demand, and 1% of greenhouse gas emissions (Tassou et al, 2008). Any reduction in their consumption will therefore be significant in terms of overall energy use. A "supermarket" is a large multiproduct retail space with a primary focus on food. There are 91,500 supermarkets in UK, and 300 new stores are opened annually (BBC, 2010).

In common with all new commercial buildings in England and Wales, a new supermarket must be designed to comply with Approved Document L2A of the Building Regulations of England and Wales (HM Government UK, 2010). Similar rules apply in Scotland and Northern Ireland. Compliance requires that the building be modeled and improved in accordance with the National Calculation Methodology (NCM)(2010). This modeling must include heat inputs from lighting, occupancy and minor electrical equipment, as well as heating, cooling and air-conditioning from HVAC systems. "Process energy" specific to the building's function is not modeled.

The building is thus designed to balance heat gains from occupancy, lighting, appliances, and solar and radiant gains and losses via fabric and ventilation, and radiant losses by supplying heating and cooling, and achieve a temperature in the required range, eg 18-25^{0}C, as shown in Figure 1.

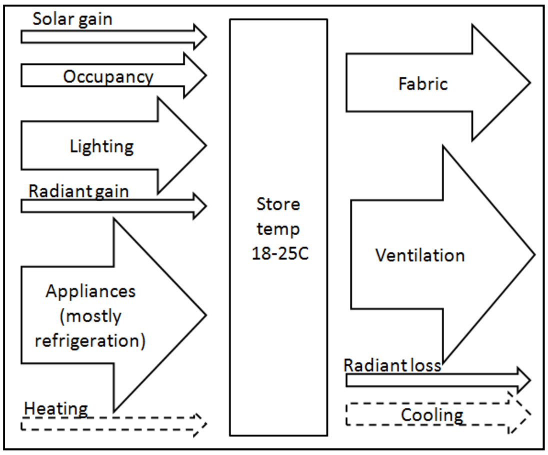

Figure 1 Balance of heat gains and losses considered in conventional design of supermarkets

In the case of supermarkets, in which refrigeration is regarded as "process energy", this means that heat transfers related to refrigerated display cabinets are not required to be included in the design calculations. Indeed, the software generally used for this purpose does not allow the inclusion of negative heat gains (losses), or for the modeling of in-store cabinets with infiltration related to door-opening.

Approved Document L2A further requires that the energy demands for heating and cooling must be reduced so that the design building (model) performs better than the notional, baseline, building (model) by a given percentage. This can be achieved by modification of these regulated components, and by use of renewables. Software tools used for building design provide methods for demonstrating compliance with Approved Document L2A as part of their overall capability, using the NCM for this purpose. Using these tools, with NCM inputs, designers therefore seek to improve the envelope of the building so as to decrease the energy demand.

Although the compliance element of a software tool is not intended as a design tool, designers consulted do use the NCM figures for energy related to electrical equipment in their calculations in the "equipment schedule". In recognition of the high energy load for refrigeration, designers seek a figure to include for this. The figure given by NCM for retail refrigeration is +25W/m^2 (NCM, 2010). This leads to the inclusion of refrigeration as a heat gain on the retail floor. If the refrigeration were like a domestic refrigerator, or a standalone cabinet in a small store, with its condenser on the back of the cabinet then this would be appropriate. However, most supermarket refrigeration is supplied from a central chiller plant with the refrigeration cabinets absorbing heat from inside the store and the central chiller condenser units dumping the heat outside the store.

In reality, as shown in Figure 2, a considerable amount of heat is lost to refrigeration (typically above 40% of the store heat balance), increasing the heating demand, and reducing the requirement for HVAC cooling very significantly.

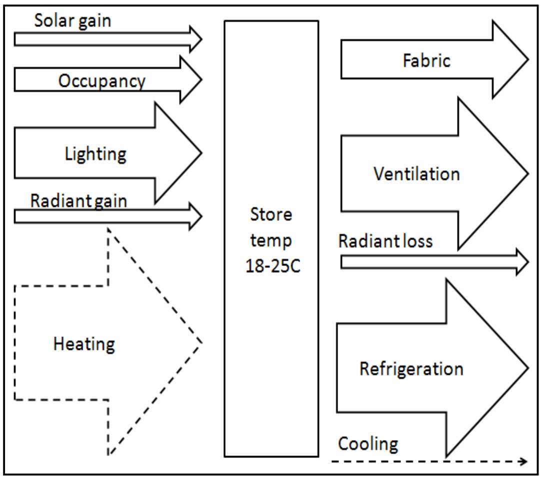

Figure 2 Heat transfers in a supermarket including heat extracted via refrigeration cabinets

This clearly leads to a very different picture for optimization.

This paper explores the impact of including thermal interactions between refrigeration cabinets and their surroundings in a model for energy demand optimization of the retail floor of a supermarket.

2. Simulation

2.1 Building envelope

The retail floor of a supermarket building, with refrigeration cabinets included, has been modeled both in Excel (Hill, 2011) and in EnergyPlus (Hill, 2012), and the results of simulations with refrigeration cabinets modeled as cold have been compared to the results of simulations with refrigeration energy entered as a heat gain. The models were based on the parameters of a newly built store in northern Manchester, optimized for compliance with Building Regulations, and simulations were run with hourly local weather data.

The retail floor was modeled as a lightweight box, with U values and ventilation rates variable as required, across the range shown in Table 1. The north facing wall was fully glazed, with an overhang for shading, and there was a clerestory window to the east. The south wall adjoined the storage, administration and technical section of the store, and was modeled as adiabatic. The retail floor was modeled with rooflights, to reflect the inclusion of rooflights on the Manchester store. The rooflight fraction was variable as required, across the range shown in Table 1. Surface emissivity and absorptivity characteristics appropriate for a polished aluminium roof, and polycarbonate sandwich rooflights were included. Thermal and light transmissivity values appropriate to the polycarbonate/nanogel sandwich were also applied (Hill, 2012).

Table 1 Design values and modeled values for ventilation rates, U values and rooflight fraction

		Design value for Manchester store	Range of values explored in modelling
Ventilation (infiltration) rate		0.36 ac/h	0.10-0.5ac/h
U values	walls	0.25 W/(m^2K)	0.05-0.5 W/(m^2K)
	roof	0.25 W/(m^2K)	0.05-0.5 W/(m^2K)
	windows	1.95 W/(m^2K)	1.95 W/(m^2K)
	rooflights	1.1 W/(m^2K)	1.1 W/(m^2K)
Rooflight fraction		8%	0% - 40%

The store was designed for natural ventilation, entailing high level extraction of air. This was not included in the modeling, as its effect would be very dependent on the effect of stratification on the retention at the top of the store of radiant gains through the roof, and stratification is not automatically modeled in EnergyPlus, and could not readily be modeled in Excel. The models assumed a fully stirred body of air in the store, though they did not include fans to achieve this. The effect of stratification would be to increase the heating demand of the store, and therefore to increase the sensitivities explored below.

2.2 HVAC, lighting and occupancy

Heating and cooling setpoints were set at 18C and 25C. Dehumidification was applied to maintain the humidity ratio at or below 7.5g/kg (equivalent to 55% relative humidity at 19C), as is considered necessary to maintain the efficiency of refrigeration cabinets. The Manchester store opens “24 hours”, and the design documents showed a lighting requirement of 900lux by day, and 400lux by night, so this was applied to the models, in which no distinction was made between days of the week. A daily occupancy profile was based on figures included in the Manchester store’s design document, and the anthropogenic heat gains were included (both sensible and latent). This profile of occupancy was subsequently applied to the refrigeration module, as customer numbers would determine the frequency of opening of cabinet doors, and therefore the heat exchange by infiltration.

2.3 Refrigeration

Refrigeration was modeled both according to the NCM, as used by compliance to Building Regulations, and with cold heat exchange at the cabinets.

2.3.1 Refrigeration set according to National Calculation Methodology

The NCM activity database specifies the input for “internal gains” from refrigeration in a food retail store as a heat gain of 25 W/m^2 for the refrigerated zone, as is appropriate for domestic fridges, where the extracted heat is dumped into the room. This was added to one variant of both models, to replicate the conventional modeling of a store.

2.3.2 Refrigeration cabinets with heat exchange

In order to explore the impact of thermal interactions between the refrigeration cabinets and the store on the heat demand of the store, a second variant was modeled with cold cabinets, with heat exchange through the fabric and by infiltration.

A mix of cabinets with and without doors, on both freezers and chillers was based on the Manchester store. Based on observation, the doors were modeled as being open for 3 seconds every minute when the store was at peak occupancy, and for reduced fractions of the time in proportion to the occupancy profile. U values were taken from design specifications or the EnergyPlus defaults, and internal temperatures were set at -20C for freezers, and 4C for chillers.

2.4 Comparison of simulation outputs to store data, and to design experience

The models only simulated the energy interactions on the retail floor of the store. The energy demands they calculated for the store were 43-55% of both the electrical and heat demand data available from the Manchester store for the whole building, including the "back area" with offices and storage areas (including chilled and frozen storage). This suggests that the modeling is broadly accurate, and useable for simulations.

Simulations run on the models with refrigeration modeled as a heat gain, on NCM figures, also give the result reported by design engineers, with an optimization saddle for ventilation and insulation at approximately 0.36ac/h and 0.25W/(m^2K), as seen on the Excel model in Figures 3 and 4. At ventilation rates below this saddle point, or higher levels of insulation (U values immediately below the saddle point), the simulation results indicate that the additional cooling need outweighs the reduction in heating load. These saddles occur at the same values as selected for optimization of the Manchester store (XXX?). This suggests that the models behave similarly to models used commercially. However, Figure 4 additionally suggests that further demand reduction appears possible at U values below 0.1W/(m^2K).

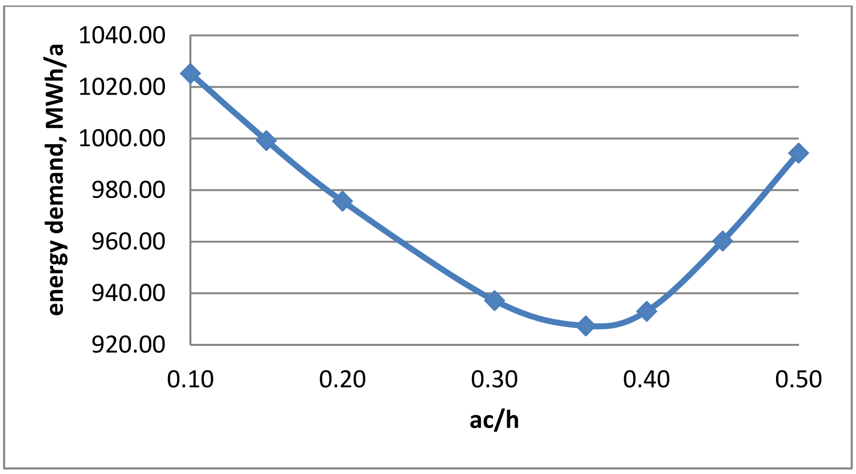

Figure 3 Variation of energy demand with ventilation rates, according to NCM model, in which refrigeration is included as a heat gain

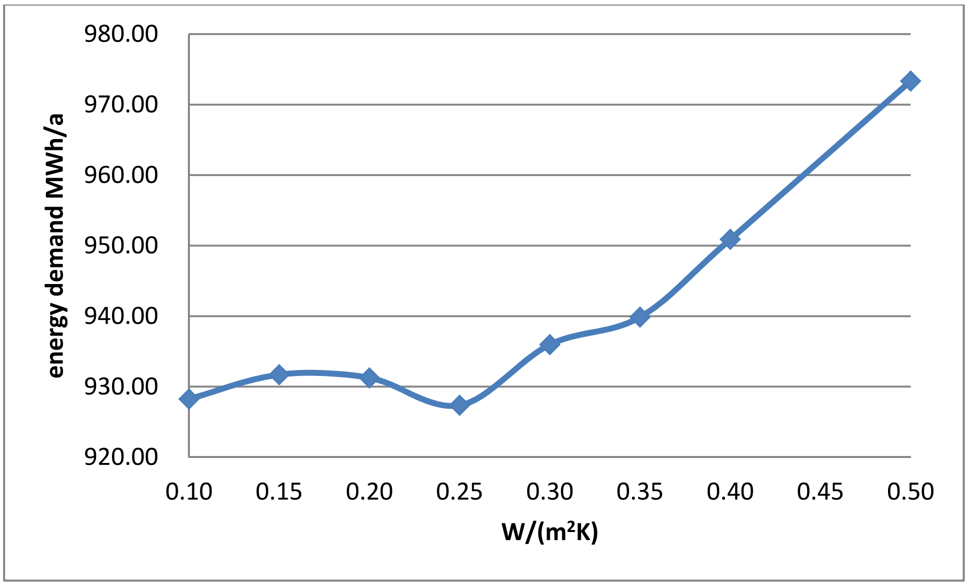

Figure 4 Variation of energy demand with insulation level, according to NCM model, in which refrigeration is included as a heat gain

3. Sensitivity analysis of energy demand of store with commercial, cold, refrigeration cabinets to envelope design

Simulations were then performed on the models with cold heat transfers at the refrigeration cabinets, to test the sensitivity of the energy demand of the retail floor to variations in the ventilation rate, insulation level, and rooflight fraction. Initially each parameter was investigated separately while keeping the others at the design values identified in Table 1.

3.1 Sensitivity to variation in ventilation rate

With cold refrigeration cabinets, the energy demand is shown by both models to have an approximately linear relationship with ventilation rate (Figure 5). Halving the ventilation rate from the conventional design value of 0.36 to 0.18 ac/h is seen on the Excel model to reduce the energy demand by 13% (230MWh/a), and by rather more on the EnergyPlus model.

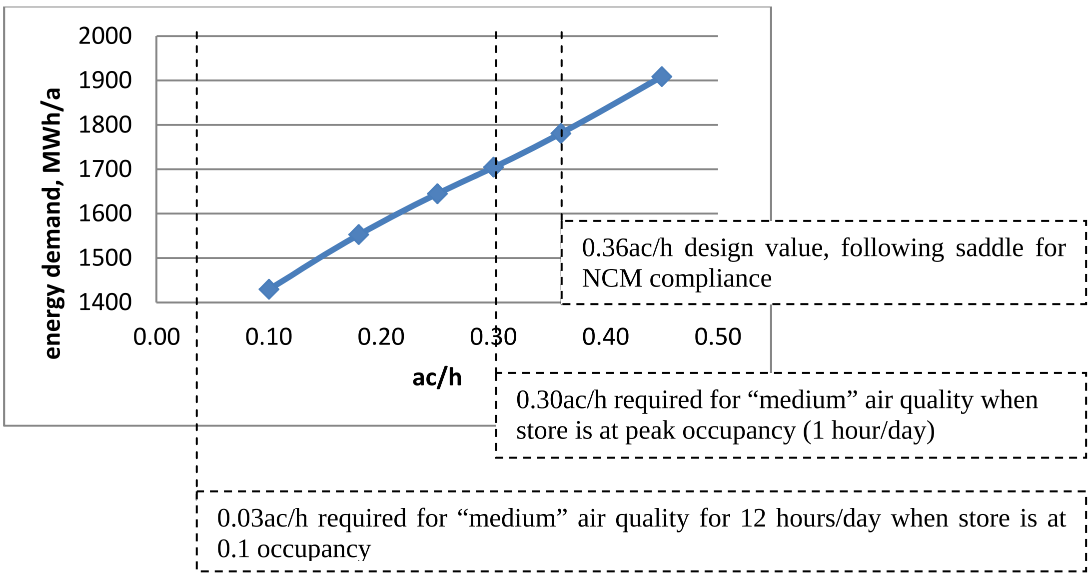

Figure 5 Sensitivity of energy demand to variation in ventilation rate, according to Excel model with cold refrigeration cabinets

This linear relationship contrasts starkly with the optimization saddle indicated by the model with NCM inputs (Figure 3). This is due to the almost entire absence of a need for cooling in the presence of refrigeration cabinets in the store. The energy demand is therefore dominated by the heating demand, and a more airtight store has a lower heating demand. It can be seen that the design value for ventilation is generous for achievement of a medium air quality for the expected maximum occupancy of the store, and exceeds by a factor of 12 the ventilation rate required for the 50% of the time when the store is at minimum occupancy.

3.2 Sensitivity to variation in level of insulation

Similarly, in the presence of cold refrigeration cabinets, the energy demand is shown by both models to have an approximately linear relationship to the level of insulation in the store envelope (figure 6). If the insulation level is doubled, from U=0.25 to U=0.125 W/(m^2K), the energy demand is seen on the Excel model to be reduced by 1.5% (25 MWh/a), and by a little more on the EnergyPlus model.

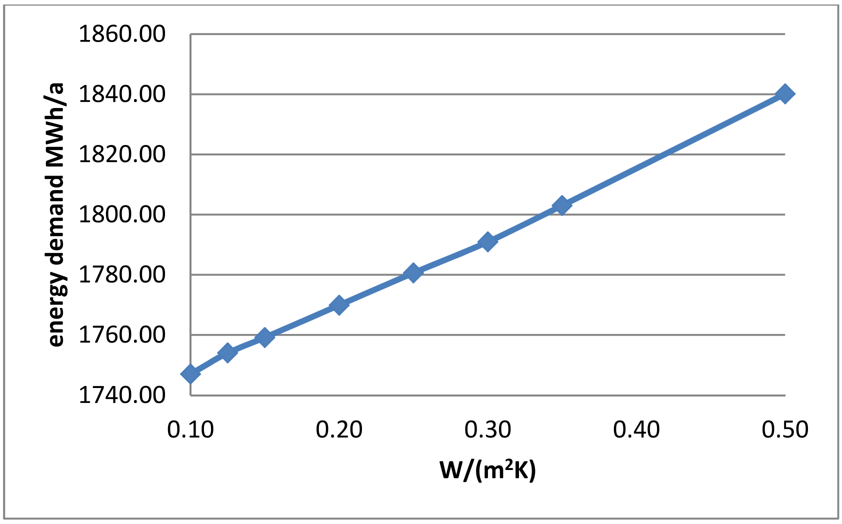

Figure 6 Sensitivity of energy demand to variation in level of insulation, according to Excel model with cold refrigeration cabinets

3.3 Sensitivity to variation in rooflight fraction

For both sets of inputs, the models show optimization saddles for a rooflight fraction around 8%. However, while with NCM inputs, the potential energy saving offered by 8% rooflights is above 12% of the total demand, the Excel model with refrigeration cabinets modeled as cold only offers a saving of 2.5% of total demand from the inclusion of rooflights.

3.4 Multivariate optimization

Combining improvements of ventilation rates with insulation levels offers further energy demand reductions, as seen in Table 2, for which energy transfers were simulated on the Excel model with refrigeration included as cold cabinets, and the level of insulation was doubled, and the ventilation rate was halved. The energy demand reduction potential indicated by parallel simulations using the EnergyPlus model is rather higher. Models can be expected to differ, but with both showing the same linear relationships, they can be assumed to indicate savings within the range of both.

Table 2 Energy demand reductions available from halving ventilation rate and doubling insulation level, as shown by Excel and EnergyPlus models

	Ventilation rate, ac/h	U value of insulation, W/(m^{2}K)	Heating energy demand, MWh/a (Excel)	Total energy demand, MWh/a (Excel)
Unimproved design	0.36	0.25	924	1781
Possible improved design	0.18	0.125	660	1519
Energy demand reduction (Excel)			29%	15%
Energy demand reduction shown by simulation using EnergyPlus			*50%*	*25%*

A further 2% reduction in energy demand would be possible by further reducing ventilation rates to 0.1ac/h at times when store occupancy is low, and the need for fresh air is therefore less (15 hours/day).

4. Conclusions

This modeling process has established that the "process energy" heat exchanges within a supermarket retail floor have a significant impact on the heat balance in the building. The operational energy demand has been found for a store whose building parameters have been optimized firstly with, and secondly without, incorporation of (cold) refrigeration heat exchanges. The store optimized with refrigeration appropriately included is found to have a 15-25% lower energy demand. This causes less CO_2 emissions than the store "optimized" according to regulations, without refrigeration ("process energy") appropriately included in the model. The energy cost reduction associated with this difference will be of the same order.

This indicates that Building Regulations, and the protocols imposed by the National Calculation Methodology are leading to significantly sub-optimized new-build supermarkets, to costly higher energy demand, and to unnecessary CO_2 emissions.

It is recommended that the Building Regulations and associated protocols should be revised to reflect the impact of process energy, where it is significant and directly affects the regulated energy, as in a supermarket, in order to minimize unwarranted CO_2 emissions.

Although the results presented in this paper relate specifically to the retail floor of a supermarket, the model could be extended to encompass the back portion of the store, with offices and storage space, some of which is chilled or frozen storage. The same principles apply to all buildings with significant process energy.

Further research is planned to assess the effects of stratification and of ventilation strategy on these findings. Additionally the impact of improvements in U values of refrigeration cabinets will be explored, along with a broader exploration of the impact of excluding process energy from design protocols for commercial buildings of different types.

ACKNOWLEDGEMENTS

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INSIGHTS INTO IMPROVING THE ENERGY PERFORMANCE OF BUILDINGS TAKEN FROM UK CASE STUDIES IN THE DOMESTIC AND EDUCATION SECTORS

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Abstract:

Buildings are responsible for significant levels of energy consumption. The increasing pressure created by regulation and legislation to reduce greenhouse gas emissions and fossil fuel consumption has led to building designers needing to radically improve the energy efficiency of buildings. The lack of information from past projects is often a barrier to the design of low energy buildings, as many organisations do not have a wide enough know how or available resource to create usable rich 'explicit *knowledge'* from the valuable concealed '*tacit knowledge'* held within the organisation. This paper describes how a new online design tool 'LESSONS' aimed at building practitioners is being developed to provide the user with easy access to both explicit and tacit knowledge gained from previous building design experience and the resulting design heuristics. The paper identifies opportunities to improve the energy performance of buildings through insights gained and lessons learnt from the content analysis of 100 case studies of completed buildings in the United Kingdom.

Keywords:

Energy efficiency; explicit knowledge; lessons learnt; design experience; tacit knowledge.

1. Introduction

The importance of sustainable building design has clearly been established by (among others) the Intergovernmental Panel on Climate Change (IPCC) and is now embodied in government legislation including the England and Wales Building Regulations, Part L, 2010. If the ambitious EU and UK government targets are to be met, the theory and practice of sustainable building design can no longer be confined to a small number of highly trained specialists (HM Government, 2009). 'LESSONS' [Bunker, 2011] is a new online design tool for building professionals that is intended to improve sustainable building design. The tool will provide the user with easy access to knowledge gained from previous sustainable building design experience and the resulting design lessons. The tool aligns well with The Soft Landings Framework (BSRIA, 2009) and the Cx (Building Commissioning) principles of collaborative working to plan, deliver and operate buildings that work as intended. (ASHRAE, 2007) The *Soft Landings Framework* (BSRIA, 2009) is a joint initiative between the UK Building Services Research and Information Association, the Usable Buildings Trust (UBT), and the originator of Soft Landings, Mark Way. The Soft Landings Framework states "there are massive gaps between client and design expectations and delivered performance".

Furthermore it recognises that a key step towards rectifying the situation is to base new designs on the real performance of previously built examples. Its purpose is to provide the structure for project teams to stay engaged after practical completion, hand-holding the client during the first months of operation to fine-tune and de-bug systems and ensure that the occupiers understand how to control and best use their new work environment. The Soft Landings process is designed to extend up to three years post-completion. It includes procedures and example checklists which act as signposts for design teams to help end-users design often unfamiliar and complex buildings. It allows for a full programme of post-occupancy evaluation that the project team can use to improve a building's performance and make it sustainable over the long term.
The Soft Landings Framework complements rather than duplicates existing procedures used by the construction industry. Specifically, it has been designed to be the underpinning framework for environmental assessments like BREEAM and LEED, all forms of energy performance certification, post-occupancy evaluation (POE), building logbooks, green leases, and industry key performance indicators (KPIs).

LESSONS aims to be a design tool/repository containing both qualitative tacit knowledge and quantitative explicit knowledge presented in a highly accessible manner. Data will be applicable to new build and retrofit projects. The initial prototype has been developed for housing and school building designs but will enable future addition of other types of buildings such as offices and retail, and other sustainable design topics such as water systems. This paper describes how the LESSONS tool is being developed to provide users with easy access to knowledge gained by other practitioners from previous building design experience and the resulting design lessons. The paper describes some of the insights and lessons learnt by the content analysis of 100 case studies of completed buildings in the United Kingdom. 75 case studies are taken from the domestic sector and 25 case studies are taken from the education sector.

2. Objectives

The objectives of LESSONS are:

- To provide building designers of all levels of expertise with initial design stage information by creating a database populated with previous designs containing both tacit and explicit knowledge;
- To augment the database with an established dynamic simulation modelling design tool featuring a simple and intuitive user interface;
- To make case study provision central to the data base; and
- To test, implement and review the usability of the design tool on real life projects.

3. Methodology

There is a clear need for more usable and holistic design tools for the next generation of buildings, and for the large scale, high efficiency retrofitting urgently needed for the existing building stock. By combining the expertise of a university with the experience and needs of diverse and experienced industrial collaborators, this can be addressed in new ways, exploiting the latest developments in software, user interface design and web technologies. Most design tools simply provide a means of performing calculations, so that designers must separately gather past design lessons from academic research papers, trade journals, design guides, in-house practice etc. This is a highly inefficient and impractical process.

The first stage of the LESSONS project was to produce a needs statement combining literature searches, a web survey and the requirements of designers within the project stakeholder group. Functional specifications of the 2 main parts of the model, the model interface and the case study database were written based on the needs statement. These have been specified from a user perspective; defining what is needed rather than how it is delivered. From this, a modeling concept has been developed translating the functional specifications into an approach that is feasible in computing terms.

Web-based design tools such as Google SketchUp have become popular with building designers since they are easier for novices to use, although these tools require a completely different approach to drawing compared with traditional Computer Aided Design (CAD).

The fast prototyping methodology is central to many innovation projects. [Stamey, 2006] The aim is to create working systems that try to solve a specific issue only – for example, to test a new interface or a new way of presenting multiple tools – and then bring the lessons learned quickly into the main development programme. For LESSONS, a fast prototype has been created and tested amongst industrial users on real projects to test specific capability and concepts. The last phase of the project is to develop a final prototype with full functionality incorporating users' experiences and feedback. It will provide a wider range of design tools and information. By making it available on the Internet and publicising it, a much broader user community will be reached. The final prototype will be used on real projects and the experience recorded. At the end of the project, exploitation will be assessed from a commercial perspective.

4. Case studies

Case study provision is central to the LESSONS data base. Contemporary documented case study material from completed building projects in the UK is in short supply; however 100 case studies have been identified and examined in detail. 75 case studies were taken from the domestic sector and 25 were taken from the education sector. Both case study sets contained information on retrofit and refurbishment projects as well as new build projects. Sources for the case studies included publications, presentations, conference material and the Internet. Key data obtained from these sources was tabulated using the following subject headings: Project reference, lesson, building type and construction, energy target, environmental assessment and performance. An example is shown in Table 1. The projects were classified into four categories: Approach, construction process, technology and wider professions. An example is shown in Table 2. The data were codified and a content analysis carried out to determine the themes highlighting positive outcomes and negative outcomes, relating to energy use. From this analysis a number of key themes (6) were identified. Finally the 100 case studies were revisited and the generic causes, both positive and negative leading to energy wastage in domestic and educational buildings were identified. These are shown in Figures 1 and 2 respectively.

Table 1 – Case study data fields domestic sector

Project reference	Lesson	Building type and construction	Location	Energy target	Environmental assessment	Performance
P001	Underestimation of timber fraction resulted in significant heat loss of 23%	Four terraced houses Timber Frame	York - UK	> ADL1B 2006 Approved Document *(as used in UK Building Regulations)*	Code for Sustainable Homes Level 6	Low carbon 19.54 $kg/m^2/yr$

Table 2 – Case study classification domestic sector

Approach	Construction process	Technology Types	Wider professions
Aspirational	Design	Natural ventilation	Management
Regulation requirement	Manufacture	High thermal mass	Infrastructure
Best practice	Construction	Ground Source pump	Transport
Innovation	Commissioning	Photovoltaic panels	Waste
Pioneering	Use	Solar thermal	Water
	Decommissioning	Wind	Biodiversity
	Refurbishment	Insulation	Other
	New Build	Glazing	
		Other	

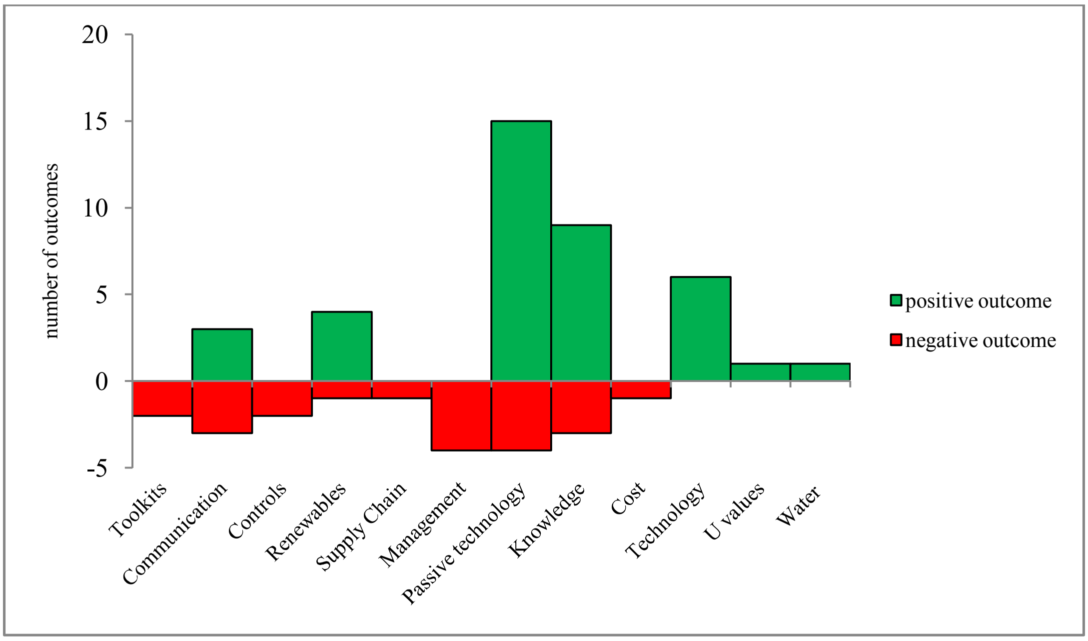

Figure 1 – Energy outcomes in the education sector

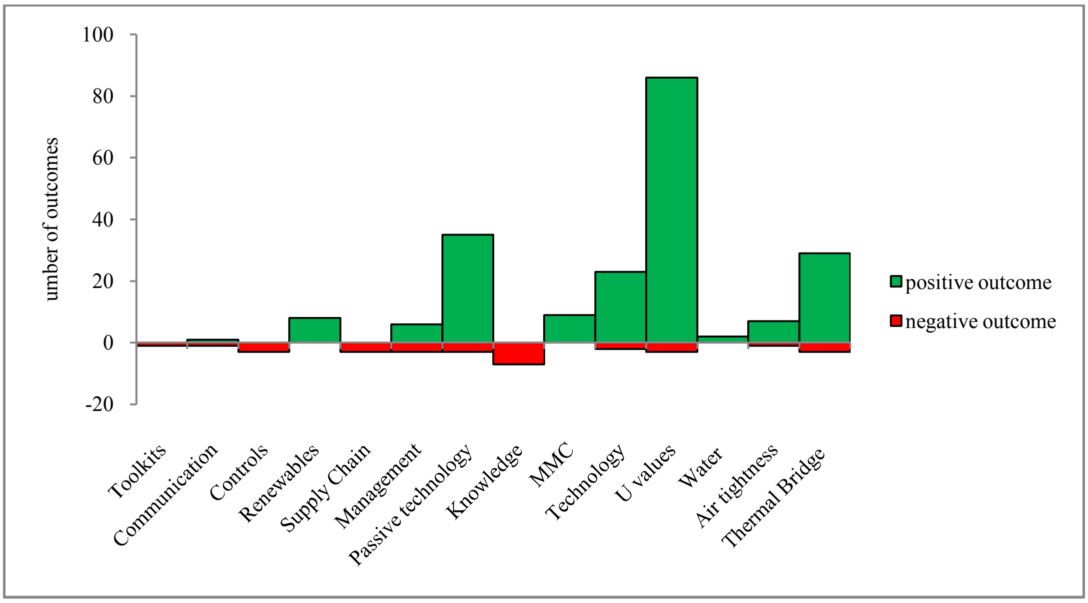

Figure 2 – Energy outcomes in the domestic sector

5. Results

As shown in Table 3, codification of the 100 case studies identified 16 areas where positive or negative causes for energy gains/outcomes were recorded. For the purpose of identification of building defects leading to energy inefficiencies these areas can be looked upon as either missed opportunity or opportunity to improve building energy efficiency. By adopting this approach we can see that the analysis has identified 296 opportunities within the sample group. If energy use is wasteful in some way then these opportunities are being squandered. Eliminating the waste, in the form of poor energy efficiency, can bring net benefits to the actual performance of a building. For example if different building techniques and knowledge flows were utilized, substantial energy savings could be gained with no loss in terms of the function of the building under consideration. From the codification of the case studies, 6 themes (Table 4) emerged that provide significant opportunities to provide a positive outcome in reducing the gap between the predicted building energy efficiency and the actual building energy inefficiency. These are; the fabric performance within the building envelope, use of passive technology, use of other technology types such as MVHR (mechanical ventilation and heat recovery), renewable energy, management and use of modern methods of construction, such as build off site techniques.

Table 3 – Case study Codification Education and Domestic Sector

Code	Education sector		Domestic sector	
Outcome	-ve	+ve	-ve	+ve
Framework and Tools	2	0	1	0
Communication	3	3	1	1
Controls	2	0	3	0
Renewable Energy	1	4	0	8
Supply Chain	1	0	3	0
Management	4	0	3	6
Passive technology	4	15	3	35
Knowledge/Skills/Craft	3	9	7	0
Cost	1	0	0	0
MMC	0	0	0	9
Technology	0	6	2	23
Material U values	0	1	3	11
Water and Biodiversity	0	1	0	2
Permeability - fabric	0	0	1	7
Thermal Bridge - fabric	0	0	3	29
Insulation - fabric	0	0	0	75
Totals	21	39	30	206
Grand total				296

Table 4 – Themes Education and Domestic Sector combined

Theme	Combined sectors		Total
Outcome	-ve	+ve	
Fabric performance	7	123	130
Passive technology	7	50	57
Technology	2	29	31
Renewable Energy	1	12	13
Management	7	6	13
MMC	0	9	9

6. Insights

Examination of the 100 case studies has provided many useful insights into opportunities to improve the energy inefficiencies of domestic and educational buildings. This section provides detailed examples of some of these insights within the first of the 6 themes – fabric performance. A systematic analysis of the content of the case studies shows that inefficiencies in this area are often due to thermal bridging, thermal mass, air tightness and insulation.

6.1. Fabric performance – Thermal Bridge

Approximately 30% of the total heat lost through a building's fabric can be as a result of thermal bridging. Furthermore, research has shown that a dwelling's annual CO2 emissions can be reduced by up to 10% with better detailing and improved air tightness. [Energy Saving Trust, 2011] Thermal bridging will happen in building envelopes when reasonably high thermal conductivity materials such as steel and concrete create pathways for heat loss that bypass the thermal insulation. When these materials provide an unbroken "short circuit" between the interior and exterior of a building, the resulting effect on the building envelope R-value, and subsequent energy loss can be large. This effect is most significant in cold climates during the winter when the indoor-outdoor temperature difference is greatest. [Elton, 2011] Besides leading to increased energy use, thermal bridges lower the internal surface temperature and are therefore sites for condensation and mould growth. Thermal bridges fall into two categories. Firstly, *Repeating thermal bridges*: e.g. timber joists, mortar joints, mullions in curtain walling. These have a significant effect on heat loss, and are required to be taken into account in the calculation of *U*-values. They are, however, rarely severe enough to cause surface temperatures to fall low enough to cause surface condensation or mould growth. Secondly, *Non-repeating bridges*: These commonly occur around openings such as lintels, jambs, sills, wall/roof junctions, and where internal walls or floors penetrate the outer building fabric. If details to minimise thermal bridges are not used, they can add 10–15% to the total heat loss from the building besides causing condensation and mould. [CIBSE Guide A, 2006]

The Elm Tree mews case study, [Bell, 2009] was of a terrace of 4 new build timber framed houses in York. It was reported that post occupancy evaluation indicated the inefficiencies with heat loss due to thermal bridging accounted for 25% of the whole heat loss. This occurred at junctions and around doors and windows. SAP is the government's standard assessment procedure for energy rating of dwellings. It is adopted by government as part of the UK national methodology for calculation of the energy performance of buildings. It is used to demonstrate compliance with building regulations for dwellings - Part L (England and Wales), Section 6 (Scotland) and Part F (Northern Ireland) - and to provide energy ratings for dwellings. Additional heat loss at junctions and around windows was assumed in the design to be the equivalent of the default value in SAP for dwelling designs that makes use of a standard catalogue of the Government's 'accredited details' [*Communities and Local Government*, 2006].

However, observations of the design and the complexity of the junctions suggested that the thermal bridging values used in designs were not appropriate. In addition, it was clear from inspection of design drawings and from observations of construction that there was a high likelihood of other thermal bypasses at certain junctions, in addition to the party wall bypass. Furthermore it was apparent from the measurements and observations that the actual U-values of the various construction elements and junctions, as-built, did not match the estimated values used in the early design phase. The estimated impact of thermal bridging and additional bypassing was an increase in heat loss equivalent to about 0.15 W/m^2K across the whole of the thermal envelope. [Bell, 2009] For codification purposes this case study clearly demonstrates energy failures relating to incorrect use of U-values, lack of tacit construction knowledge shown by the reliance of SAP default values and poor design detailing leading to excessive thermal bridging.

6.2. Fabric performance – Air Tightness

Air tightness is a measure of the resistance of the building envelope to inward or outward air leakage. It is caused by pressure differences due to wind or hot air rising (stack) producing positive and negative pressure on the envelope and mechanical ventilation systems. It has been shown to represent the single largest source of heat loss and gain through the building envelopes of nearly all types of buildings. ‘Tests carried out by the National Research Council of Canada on high-rise commercial and residential buildings, schools, supermarkets and houses have shown levels of 30 to 50 % of heat loss could be attributed to air leakage.’ [Knutson, 2008] Studies conducted on a typical modern Finnish detached house in Finland indicate infiltration causes about 15–30% of the energy use of space heating (including ventilation) [Jokisalo, 2007] Pressure testing of the completed buildings at Elm Tree Mews achieved air tightness values that are typical of current UK housing. Figure 5 compares the air tightness achieved at Elm Tree Mews with air tightness distributions from a sample of dwellings constructed to the 2002 regulations (Grigg, 2004), 2006 regulations (NHBC, 2008) and from the Stamford Brook low energy field trial (Wingfield, *et al.*, 2008) It is clear that, for a low energy scheme, the air tightness performance at Elm Tree Mews was well above the range expected, even for a moderately efficient scheme such as Stamford Brook, which had a target specification of 5 $m^3/(h.m^2)$. Also, it is anticipated that levels of air tightness are likely to deteriorate as the dwellings mature. At Elm Tree Mews the air tightness target was not made explicit in the detailed design documentation, despite the initial aspirations of achieving a relatively low figure of 3 $m^3/(h.m^2)$. The lack of an explicit target and detailed design for air tightness resulted in values that are above those that would be expected for a low energy housing scheme. If the target of 3 $m^3/(h.m^2)$ had been maintained, the heat loss from air leakage would have been approximately 50 per cent lower (13 W/K) than the measured value and approximately 70% (31 W/K) lower than the nominal value used in the Building Regulations SAP submission. However, it is likely that to obtain the benefit of low air permeability and to guarantee adequate indoor air quality, a change to the ventilation system would have been required, incorporating high performance heat recovery ventilation.

Some of the difficulties reported in the case study were directly related to the complexity of the geometry and the difficulties of maintaining a continuous air barrier at junctions. The complexity of the roof design and the detailing of the dormer windows resulted in the formation of small voids at junctions. The intermediate floor between the first and second floors is shown in Figure 4. This is a difficult junction to design in terms of air tightness since maintaining continuity of the air barrier at this point would require some careful consideration of the design of the air barrier, selection of appropriate materials and careful sequencing. Perhaps the simplest solution in this case would have been to design the junction with a membrane that wraps the end of the intermediate floor so that it could have been linked with the internal air barriers, together with an appropriate series of construction steps planned to ensure correct installation of the membrane. “The issue here is not that the aesthetic requirements of the scheme should be unduly sacrificed but, rather, that the impact on the detail design of air tightness needs to be understood and design resources applied accordingly.” [Bell, 2009]

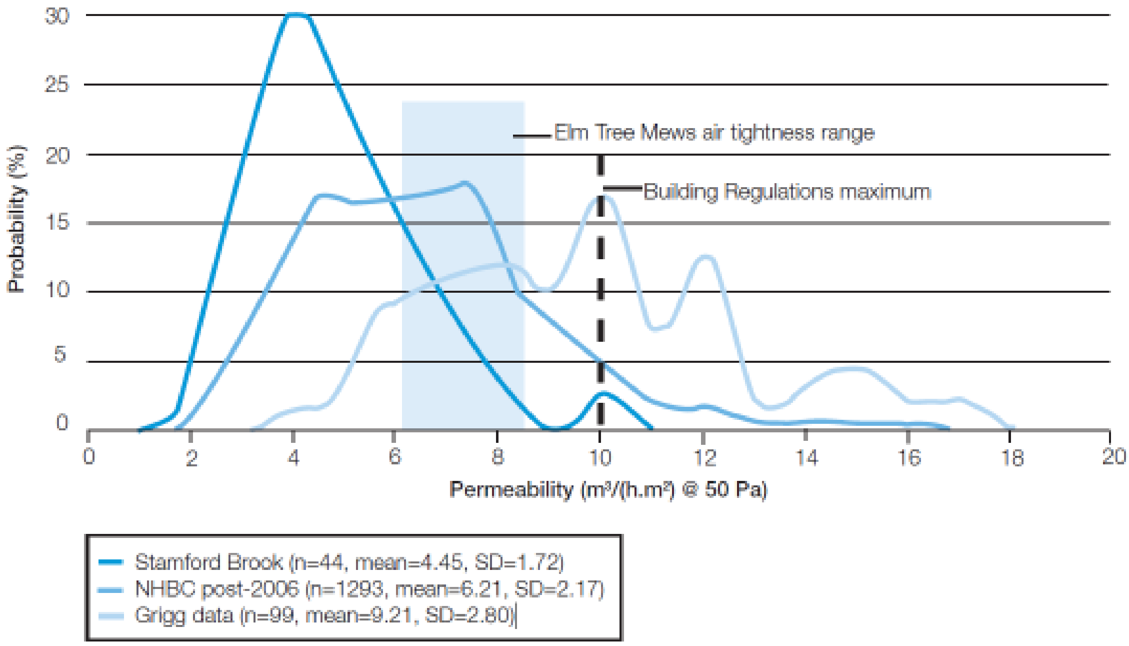

Figure 3 – Elm Tree Mews air tightness compared with post 2002 and 2006 regulatory regimes and the Stamford Brook Low Energy Masonry Scheme (Bell, 2009)

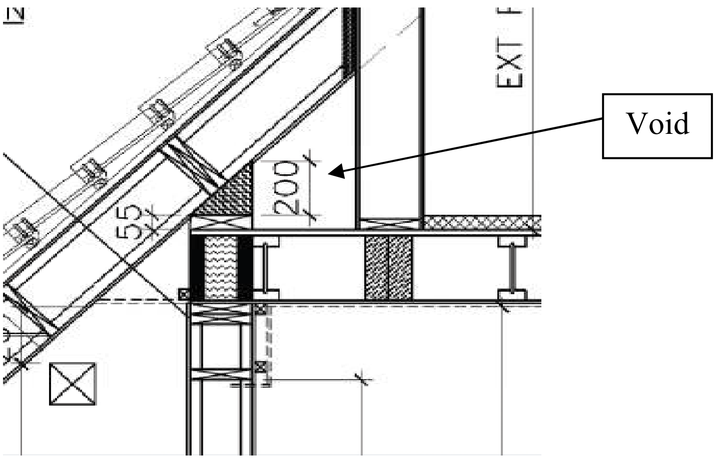

Figure 4 - First floor and dormer window junction (Bell, 2009)

The design requirement of air tightness has important implications not only for thermal performance but also for the design of the ventilation system. It was reported that at Elm Tree Mews, following analysis of the design documentation and observation of the construction process, it seems that air tightness did not feature as an important design criterion. However, even with the lack of any explicit design for air tightness there was a possibility that the scheme might have been air tight purely by chance. If this had been the case, it is likely that the designed ventilation system (which comprised intermittent extractor fans in kitchens and bathrooms and manually operated trickle vents) would not have provided adequate indoor air quality. For codification purposes this case study clearly demonstrates a negative energy outcome because not enough consideration was given at the initial design stage to the complex roof design and dormer windows. This area ultimately would prove hard to make airtight by way of a continuous air barrier.

7. Conclusions

A systematic analysis of the content of the 100 case studies shows that there are many opportunities to improve the energy performance of buildings in the domestic and education sectors. The 6 themes that emerged from this study where energy performance can be improved are: Fabric performance, use of passive technology, technology (such as MVHR), renewable energy, management and modern methods of construction.

The 3 interventions that will have the biggest impact on energy reduction are the provision of insulation, the reduction in thermal bridging and the use of passive technology.

There is further opportunity to reduce the energy demand of buildings through the use of technology such as MVHR. Throughout the study the importance of attention to detail in the initial design stage has frequently been mentioned. Failure to do so has lead to some apparently fairly trivial decisions and design changes resulting in large impacts on the energy performance of buildings.

The development of the LESSONS tool compliments The Soft Landings Framework and has provided a starting point for the development of the much richer ontology required by the global community to assist building professionals in their search to improve the energy performance of buildings.

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The LESSONS tool can be accessed at: www.buildinglessons.com

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Two Similarity Measure Approaches to Whole Building Fault Diagnosis

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Abstract:
This paper introduces two methods based on cosine similarity and Euclidean distance similarity respectively to diagnose possible causes of abnormal whole building energy consumption. The concepts of cosine similarity and Euclidean distance similarity are defined and the methodology for implementing the proposed whole building fault diagnosis approaches is presented. Cosine similarity and Euclidean distance similarity are applied to two field observed fault test cases, and both the cosine similarity and Euclidean distance similarity methods indicated that the most probable fault was the fault observed in the field survey.

Keywords:
Energy consumption; Cosine angle; Euclidean distance; Fault diagnosis; Similarity measure

1. Introduction

In the U.S., faults in HVAC systems can increase HVAC energy consumption by 30% (Brambley et al. 1998). Hence Fault Detection and Diagnosis (FDD) in building HVAC systems is of significant interest. There are two fundamental approaches to FDD in buildings: a component level (bottom-up) approach and a whole building (top-down) approach (Seem 2007). The component level approach focuses on faults in individual systems such as air-handling units, variable-air-volume boxes, meters, chillers, or boilers. The whole-building approach specializes in abnormal behavior in global-level measurements such as the whole building cooling, heating or electrical consumption. Most HVAC FDD studies focus on components, but several whole-building FDD studies are summarized below.

Haberl et al. (1989) introduced a three-parameter, steady–state model to predict the energy consumption. A fault is identified when the absolute residual between the actual and predicted consumption exceeds a specified deviation. Friedman and Piette (2001) illustrated a whole building FDD tool, which uses a daily energy consumption index to show if the actual energy consumption was higher than normal, normal or lower than normal. Seem (2007) described a method for detecting abnormal energy consumption in buildings. The method uses outlier detection to determine if the energy consumption for a particular day is significantly different than previous energy consumption.

Lee and Claridge (2007) examined the use of the ASHRAE Simplified Energy Analysis Procedure (SEAP) for fault detection at the whole-building level. The calibrated SEAP model is used to predict the cooling and heating consumption during a post-commissioning period. The model is established and calibrated based on the building chilled water (CHW) and hot water (HW) consumption in the baseline period chosen from a post-commissioning time period when the building's operation is considered to be optimal. Curtin (2007) developed a prototype of the Automated Building Commissioning Analysis Tool (ABCAT) following the system of Lee and Claridge (2007). The "Cumulative Cost Difference" plot is applied as the primary fault detection metric. A SDVAV w/Economizer Rules for Diagnostic Clarifier was proposed in the thesis for fault diagnosis.

The papers reviewed above show that most whole building FDD research or tools developed have focused on fault detection. They identified abnormal consumption and may estimate the cost of any abnormality identified. A general scheme to diagnose fault is seldom mentioned in the studies reviewed. In practice, it is meaningful to find a diagnostic method to indicate the possible cause(s) for the detected abnormal energy consumption. Narrowly classifying a fault into a subset of possible causes would help the operator or technician find the specific cause of a fault and correct it more quickly and efficiently.

Similarity measures are widely used in pattern matching. They quantitatively represent the degree of compliance within vectors. Similarity measures have shown effectiveness in FDD in many industries (Yoon and MacGregor 2001, Li and Dai 2005, Huang et al. 2007, Kabir 2009, Lee et al. 2009). According to McGill et al. (1979), there are more than 60 different similarity measures. Among them, the most popular are cosine similarity and Euclidean distance similarity.

Two approaches for whole building fault diagnosis based on cosine similarity and Euclidean distance similarity respectively are presented in this paper. The level of diagnostics proposed emphasizes limiting the possible causes to several options and ranking the options according to their probabilities. It will not attempt to "find a needle in a haystack", but instead will attempt to effectively reduce the size of the haystack in which the operator must look. This paper first introduces the concepts of cosine similarity and Euclidean distance similarity, next presents the methodology of the proposed whole building fault diagnosis approaches, and then demonstrates the results of two field test cases.

2. Similarity Measures

2.1. Cosine Similarity

Cosine similarity is a fundamental angle-based measure of similarity between two vectors of n dimensions using the cosine of the angle between them (Candan and Sapino 2010). It measures the similarity between two vectors based only on the direction, ignoring the impact of the distance between them. Given two vectors of attributes, $X = (x_1, x_2, \dots, x_n)$ and $Y = (y_1, y_2, \dots, y_n)$, the cosine similarity, $\cos\theta$, is represented using a dot product and magnitude as

$$\cos\theta = \frac{X \cdot Y}{\|X\|\|Y\|} = \frac{\sum_{i=1}^{n} x_i y_i}{\sqrt{\sum_{i=1}^{n} x_i^2}\sqrt{\sum_{i=1}^{n} y_i^2}} \quad (1)$$

The resulting similarity ranges from -1 meaning exactly opposite in direction, to 1 meaning exactly the same, with 0 indicating independence, and intermediate values indicating intermediate similarity or dissimilarity.

2.2. Euclidean Distance Similarity

Euclidean distance similarity is a common distance-based measure of similarity between two vectors of n dimensions using the distance between the vectors (Candan and Sapino 2010).

The distance-based similarity measure considers only the impact of the distance between vectors, regardless of the direction of the vectors. Given two vectors of attributes, $X = (x_1, x_2, \dots, x_n)$ and $Y = (y_1, y_2, \dots, y_n)$, the Euclidean distance d from vector X to Vector Y is

$$d(X,Y) = \sqrt{(x_1 - y_1)^2 + (x_2 - y_2)^2 + \dots + (x_n - y_n)^2} = \sqrt{\sum_{i=1}^{n}(x_i - y_i)^2} \quad (2)$$

Shepard (1987) proposed as a universal law that Euclidean distance d and perceived Euclidean distance similarity s are related via an exponential function

$$s(X,Y) = e^{-d(X,Y)} \quad (3)$$

The resulting similarity ranges from 0 to 1 with 1 meaning the two vectors are identical.

3. Methodology

Fig.1 displays the major steps required to diagnose abnormal cooling and heating consumption in buildings using similarity measures. The method is referred to as the cosine similarity method if cosine similarity is adopted and is referred to as the Euclidean distance similarity method if Euclidean distance similarity is implemented.

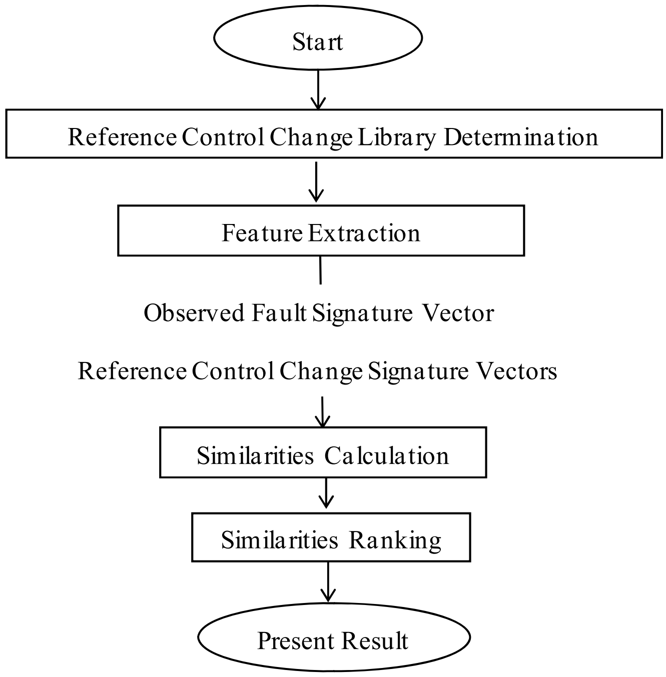

Fig. 1 Block diagram for diagnosing abnormal energy consumption

Step 1: Reference Control Change Library Determination

Whole building fault diagnosis is different from component level fault diagnosis. It can only give a general clue, for example, that there is excess outside air flow in the building, but can't tell which specific component, e.g. the fully closed outside air damper of AHU 3-1, is causing the problem. A technician still needs to investigate in the field to determine and correct the specific cause. The reference control change library collecting known whole building level faults is pre-determined initially. Table 1 gives ten whole building level fault examples. Each fault listed in Table 1 will be called a reference control change in the subsequent discussion.

Table 1: Whole building level fault examples

Outside air flow volume increase/decrease
Preheat/precool temperature increase/decrease
Preheat/precool coil valve leakage
Cooling coil (SD)/cold deck (DD) leaving temperature increase/decrease
Hot deck (DD) leaving temperature increase/decrease
Heating coil valve leakage (DD)
Minimum airflow volume increase/decrease
Maximum airflow volume (CV) increase/decrease
Room set-point temperature increase/decrease
Terminal box damper leakage (DD)

Note: SD – Single Duct System; DD – Dual Duct System; CV – Constant Volume System

The signatures of the reference control changes are used as the reference symptoms in fault diagnosis. The energy pattern may be different when the control change severity is different, so the number of levels of severity for a control change will be defined in advance in the library.

Step 2: Feature Extraction

The feature extraction block generates the observed fault signature vector and a number of reference control change signature vectors, each corresponding to a known control change in the reference control change library.

It is assumed some fault detection mechanism has already determined that an abnormal consumption fault is present and has persisted for a certain time. This period is referred as the fault period. In this block, first, the calibrated simulation model in ABCAT is used to produce the fault-free cooling and heating consumption in the fault period. Second, the calibrated simulation model in ABCAT is used to predict the cooling and heating consumption when there is a known control change from the reference library persisting during the fault period. For a specified control change, a specific input parameter of the calibrated simulation model will be changed. Since there are several levels of severity for a control change, the corresponding input parameter will be changed several times to simulate various fault sizes. Finally, the observed fault signature vector and reference control change signature vectors are generated using the following expression:

$$\mathrm{V} = \begin{bmatrix} \mathrm{fs_{CHW}} \\ \mathrm{fs_{HW}} \end{bmatrix} \quad (4)$$

where $\mathrm{fs_{CHW,i}} = \frac{\mathrm{CHW_{mea,i}} - \mathrm{CHW_{sim,i}}}{\mathrm{E_{AveBaseline}}}$, $\mathrm{fs_{HW,i}} = \frac{\mathrm{HW_{mea,i}} - \mathrm{HW_{sim,i}}}{\mathrm{E_{AveBaseline}}}$ (Observed fault)

$\mathrm{fs_{CHW,i,j}} = \frac{\mathrm{CHW_{ref\,C,i,j}} - \mathrm{CHW_{sim,i}}}{\mathrm{E_{AveBaseline}}}$, $\mathrm{fs_{HW,i,j}} = \frac{\mathrm{HW_{ref\,C,i,j}} - \mathrm{HW_{sim,i}}}{\mathrm{E_{AveBaseline}}}$ (Reference control change)

A signature vector includes two parts: the CHW signature f_{sCHW} and the HW signature fs_{HW}. In this way, the similarity of both CHW and HW features can be considered. $CHW_{mea,i}$ and $HW_{mea,i}$ are the daily measured cooling and heating energy consumption values respectively on the i^{th} day of the fault period; $CHW_{sim,i}$ and $HW_{sim,i}$ are the daily fault-free cooling and heating energy consumption values respectively predicted by the calibrated simulation model on the ith day of the fault period. $CHW_{ref\ C,i,j}$ and $HW_{ref\ C,i,j}$ are the daily cooling and heating energy consumption values respectively on the ith day of the fault period when there is the jth control change from the reference library persisting during the fault period. $E_{AveBaseline}$ is the average cooling plus heating energy consumption values in the baseline period. Assuming the fault severity has five levels in the reference library, there would be five reference control change signature vectors for a single reference control change.

Step 3: Similarities Calculation

In this block, cosine similarity and Euclidean distance similarity between the observed fault signature vector and each of the reference control change signature vectors are calculated. X in expressions (1-3) is the observed fault signature vector and Y is the reference control change signature vector. Substituting the expressions of observed and reference signatures, the expressions for cosine similarity cosθ and Euclidean distance similarity S (X, Y) become

$$\cos\theta = \frac{\sum_{i=1}^{n}[(CHW_{mea}-CHW_{sim})_i(CHW_{ref\ C}-CHW_{sim})_i+(HW_{mea}-CHW_{sim})_i(HW_{ref\ C}-HW_{sim})_i]}{\sqrt{[\sum_{i=1}^{n}[(CHW_{mea}-CHW_{sim})_i^2+(HW_{mea}-HW_{sim})_i^2]}\sqrt{[\sum_{i=1}^{n}[(CHW_{ref\ C}-CHW_{sim})_i^2+(HW_{ref\ C}-HW_{sim})_i^2]}} \quad (5)$$

$$S(X,Y) = e^{-\sqrt{\sum_{i=1}^{n}\frac{(CHW_{mea}-CHW_{ref\ C})_i^2}{E_{AveBaseline}}+\sum_{i=1}^{n}\frac{(HW_{mea}-HW_{ref\ C})_i^2}{E_{AveBaseline}}}} \quad (6)$$

where i is the ith day in the fault period and n is the number of days in the fault period. If the reference control change doesn't cause any energy shift over the fault period, $CHW_{ref\ C}$ and $HW_{ref\ C}$ would be the same as CHW_{sim} and HW_{sim} respectively. In this context, the cosine similarity is defined as zero.

Step 4: Similarities Ranking

Similarities ranking block would sort different types of reference control changes by the similarity in descending order. As mentioned above, a reference control change would have more than one fault signature vector. Thus, two steps will be taken when ranking the similarities. First, choose the largest cosine similarity/Euclidean distance similarity from the cases with the same reference control change to be representative of that control change. Next, compare the representative similarities of all the reference control changes and sort them by descending order to create a rank-ordered list of control changes.

Step 5: Present Results

The rank-ordered list of control changes basically ranks the probability that the reference control change is the cause of the observed fault. The similarity measures compare the symptoms of the current fault against the symptoms of the reference control changes. A larger similarity corresponds to a higher probability that the known control change is the cause of the observed abnormal consumption.

4. Field Test Case 1 – Sbisa Dining Hall

4.1. Building Information and Field Data Sets

Sbisa Dining Hall is an 82,000 ft^2 single story building with a partial basement on the campus of Texas A&M University in College Station, TX. Its primary function is as a dining facility. The main AHUs are single duct constant volume (SDCV) AHUs with terminal reheat boxes. Three constant volume dedicated outside air handling units (OAHUs) provide pretreated makeup air for the majority of the AHUs. The ABCAT simulation was calibrated to the baseline consumption period of February 2, 2004 to December 31, 2004.

The field investigation discovered exceptionally low discharge air temperature in two of the three OAHUs in the building in 2006 (Curtin 2007). The investigated fault period is January 1-June 4, 2006. The maximum monthly average cooling and heating consumption increase in the fault period is 15% of the average energy consumption in the baseline period (76.8MMBtu/day) (Fig.2).

Monthly average energy (cooling and heating) use change index in Fig.2 is defined as

$$\text{Monthly average energy use change index} = \frac{\text{Monthly average energy use change}}{\text{Daily average energy use in the baseline period}} \quad (7)$$

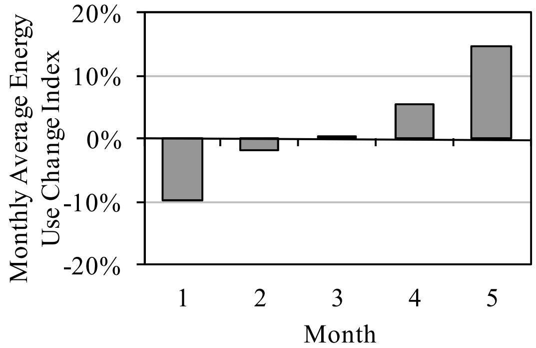

Fig.2 Monthly average energy (cooling plus heating) consumption changes in the period of 1/1/2006-6/4/2006 for the Sbisa Dining Hall

Reference Control Change Library**Error! Reference source not found.**Table 2 defines 12 different types of reference control change and there are five levels (I - VI) of fault severity for each control change. Each row shows a type of reference control change. Column one indicates the ID of the reference control change. Column two provides the key words describing the control change. The remaining columns present the different magnitudes of the control change. For example, "-10%" in the first row means outside airflow ratio decreased 10% and "10%" in the second row means outside airflow ratio increased 10%. The magnitudes III, IV, and V of control change "X_{oa} decrease" are blank; they would have negative values since the original input parameter was 28% in the calibrated simulation model.

Table 2: Reference control change library for the Sbisa Dining Hall

ID	Reference Control Change	Magnitude					Units
		I	II	III	IV	V	
1	X_{oa} decrease	-10%	-20%				
2	X_{oa} increase	10%	20%	30%	40%	50%	
3	T_{prec} decrease	-2	-4	-6	-8	-10	°F
4	T_{prec} increase	2	4	6	8	10	°F
5	T_{cl} decrease	-2	-4	-6	-8	-10	°F
6	T_{cl} increase	2	4	6	8	10	°F
7	X_{max} decrease	-10%	-20%	-30%	-40%	-50%	
8	X_{max} increase	10%	20%	30%	40%	50%	
9	T_{rc} decrease	-2	-4	-6	-8	-10	°F
10	T_{rc} increase	2	4	6	8	10	°F
11	T_{rh} decrease	-2	-4	-6	-8	-10	°F
12	T_{rh} increase	2	4	6	8	10	°F

Note: X_{oa} – Outside airflow ratio; T_{prec} – Outside air precooling temperature; T_{cl} – Cooling coil air leaving temperature; X_{max} – Maximum airflow ratio; T_{rc} – Room cooling set-point temperature; T_{rh} – Room heating set-point temperature.

4.2. Diagnostic Results with Field Test Data

The proposed cosine similarity and Euclidean distance similarity methods were applied in the fault period. The observed fault signature vector components are plotted versus outside air temperature in Fig.3.

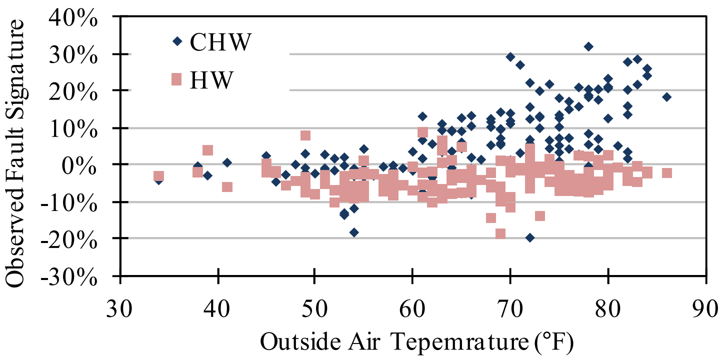

Fig.3 The observed fault signature vector components plotted as a function of outside air temperature in the period of 1/1/2006-6/4/2006 for the Sbisa Dining Hall

Fig.4 shows control changes ordered in descending order of the representative cosine similarity of the type of reference control change. In Fig.4, the first bar on the left has the highest cosine similarity, and the last bar on the right has the lowest cosine similarity. The reference control change IDs on the X axis correspond to the IDs in Table 2. Fig.4 shows that the control changes "T_{prec} decrease" and "X_{oa} decrease" have the largest and smallest cosine similarity respectively among the 12 kinds of reference control change. Therefore, the energy pattern of the control change "T_{prec} decrease" is most similar to the energy pattern of the observed fault. The observed abnormal consumption is most likely due to a decrease of the outside air precool temperature and is least likely to be caused by a decrease of outside airflow ratio. Similarly, the ranking of reference control changes based on the results of Euclidean distance similarity concludes that the decrease of outside air precool temperature is the most probable reason for the observed fault (Fig.5).

Curtin (2007) reported that investigation into trended control data points had led to the discovery of exceptionally low discharge air temperature in two of the three OAHUs in the building. It is obvious that the diagnosis result with either the cosine similarity or Euclidean distance similarity method is consistent with the field investigation conclusion.

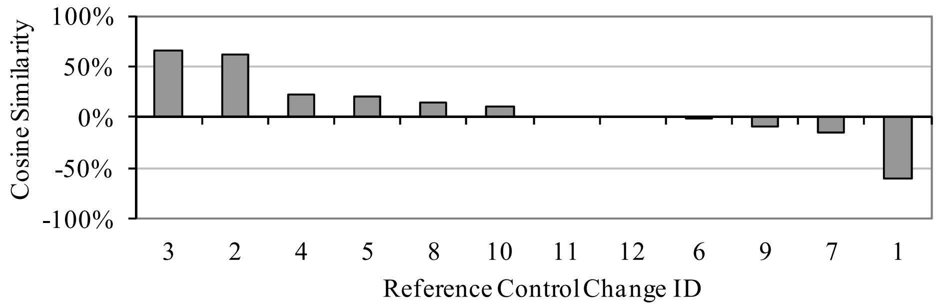

Fig.4 Representative cosine similarity for different reference control changes sorted in descending order for the Sbisa Dining Hall

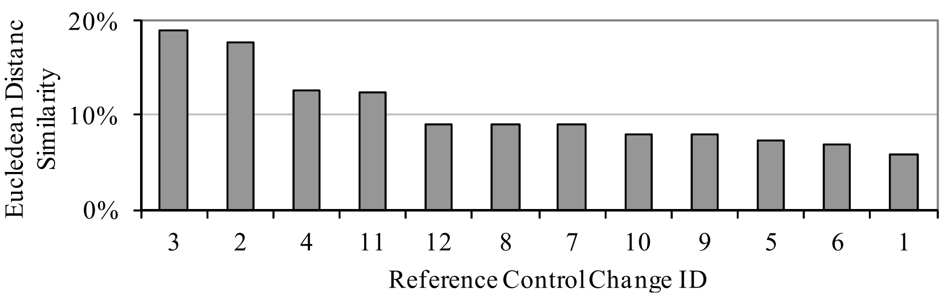

Fig.5 Representative Euclidean distance similarity for different reference control changes sorted in descending order for the Sbisa Dining Hall

5. Field Test Case 2 – Bush Academic Building

5.1. Building Information and Field Data Sets

Bush Academic Building is located on the west campus of Texas A&M University in College Station, TX. It consists primarily of offices and classrooms. The building has three floors for a total area of 133,326 ft^2. It is generally occupied on weekdays during the day. The HVAC system in the building is a DDVAV system. The ABCAT simulation was calibrated to the baseline consumption period of weekdays from June 01, 2007 to April 20, 2008.

The targeted fault period is weekdays from November 1, 2008 to June 30, 2009. The field inquiry indicates that there was a preheat valve leaking by on a pre-treat unit during the fault period (Claridge et al. 2009). The maximum monthly average cooling and heating consumption increase in the fault period is 30% of the average energy consumption in the baseline period (21.7MMBtu/day) (Fig.6).

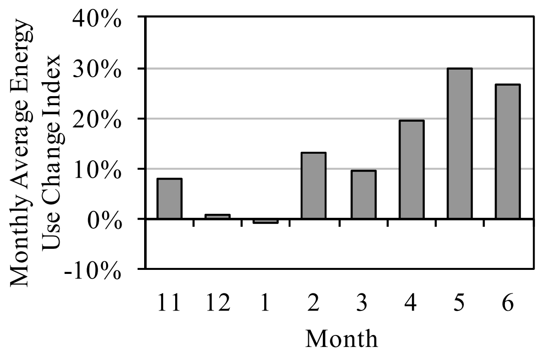

Fig.6 Monthly average energy (cooling plus heating) consumption changes for the weekday period of 11/1/2008-6/30/2009 for the Bush Academic Building

5.2. Reference Control Change Library

Seventeen different types of reference control change with five levels of magnitude are presented in Table 3.

Table 3: Reference control change library for the Bush Academic Building

ID	Reference Control Change	Magnitude					Units
		I	II	III	IV	V	
1	X_{oa} decrease	-2%	-4%	-6%	-8%	-10%	
2	X_{oa} increase	2%	4%	6%	8%	10%	
3	T_{preh} decrease	-3	-6	-9	-12	-15	°F
4	T_{preh} increase	3	6	9	12	15	°F
5	PreHL increase	10	20	30	40	50	kBtu/hr
6	T_{cl} decrease	-2	-4	-6	-8	-10	°F
7	T_{cl} increase	2	4	6	8	10	°F
8	T_{hl} decrease	-2	-4	-6	-8	-10	°F
9	T_{hl} increase	2	4	6	8	10	°F
10	HL increase	10	20	30	40	50	kBtu/hr
11	X_{min} decrease	-2%	-4%	-6%	-8%	-10%	
12	X_{min} increase	2%	4%	6%	8%	10%	
13	T_{rc} decrease	-2	-4	-6	-8	-10	°F
14	T_{rc} increase	2	4	6	8	10	°F
15	T_{rh} decrease	-2	-4	-6	-8	-10	°F
16	T_{rh} increase	2	4	6	8	10	°F
17	TDL increase	2%	4%	6%	8%	10%	

Note: X_{oa} – Outside airflow ratio; T_{preh} – Outside air preheating temperature; PreHL – Heat leakage of preheat coil; T_{cl} – Cold deck air leaving temperature; T_{hl} – Hot deck air leaving temperature; HL – Heat leakage of heating coil; X_{min} – Minimum airflow ratio; T_{rc} – Room cooling set-point temperature; T_{rh} – Room heating set-point temperature; TDL – Terminal box damper leakage.

5.3. Diagnostic Results with Field Test Data

The proposed cosine similarity and Euclidean distance similarity methods are implemented in the fault period. The observed fault signature vector components are plotted versus outside air temperature in Fig.7.

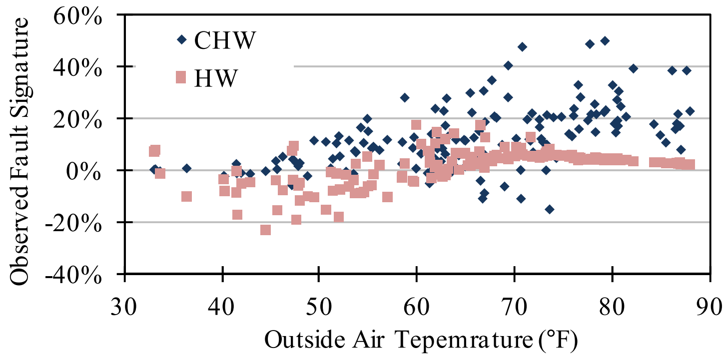

Fig. 7 The observed fault signature vector components plotted as a function of outside air temperature in the weekday period of 11/1/2008-6/30/2009 for the Bush Academic Building

Fig.8 indicates that the cosine similarity values for the observed fault and reference control changes “Heat leakage of preheat coil increase” (ID 5) and “Heat leakage of heating coil increase” (ID 10) are almost identical and rank in the top two places among the 17 reference control changes. This suggests that control changes “Heat leakage of preheat coil increase” and “Heat leakage of heating coil increase” are the two most similar energy change patterns to the energy change pattern of the observed fault. They are the two most probable causes of the observed abnormal energy consumption.

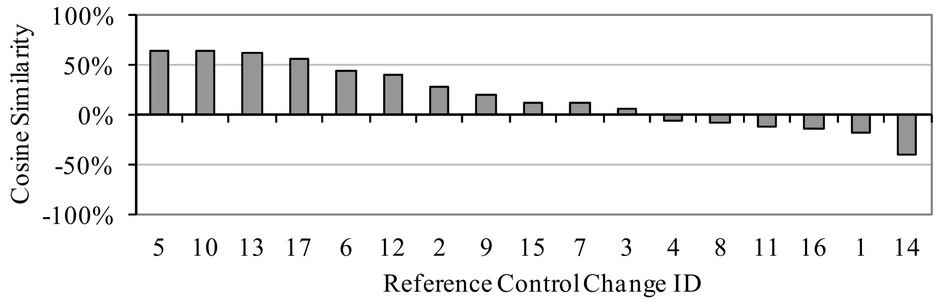

Fig.8 Representative cosine similarity for different reference control changes sorted in descending order for the Bush Academic Building

The difference between the Euclidean distance similarity values of the different reference control changes range from 3% to 7% (Fig.9). The control change “Heat leakage of preheat coil increase” (ID 5) has the largest Euclidean distance similarity value. The small value of Euclidean distance similarity is rooted in its definition. Fig.10 demonstrates that the Euclidean distance similarity exponentially falls with the increase of Euclidean distance. When Euclidean distance is 0.1, Euclidean distance similarity is 90%, and when Euclidean distance is 3, the similarity drops to only 5%. The Euclidean distance among the observed fault vector and all pre-determined reference control change vectors are above 2; thus the corresponding Euclidean distance similarities based on expression (3) are all below 10%.

Both the cosine similarity and Euclidean distance similarity methods indicate the control change “Heat leakage of preheat coil increase” has the highest similarity and thus is considered to be the most probable reason for the observed abnormal energy consumption. The field inquiry indicates that there was a preheat valve leaking by on a pre-treat unit during the fault period (Claridge et al. 2009). The fault diagnosis results are consistent with the field inspection conclusion.

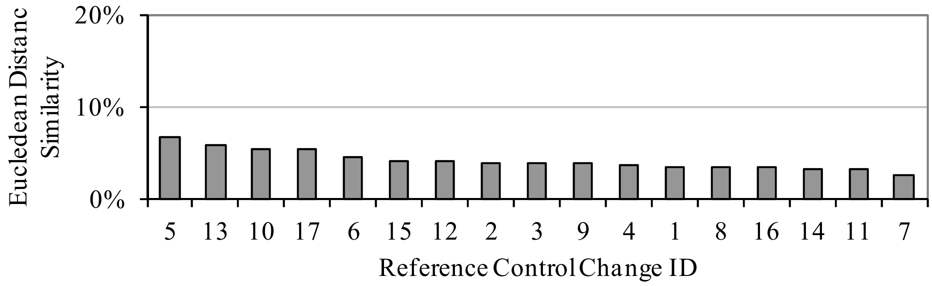

Fig.9 Representative Euclidean distance similarity for different reference control changes sorted in descending order for the Bush Academic Building

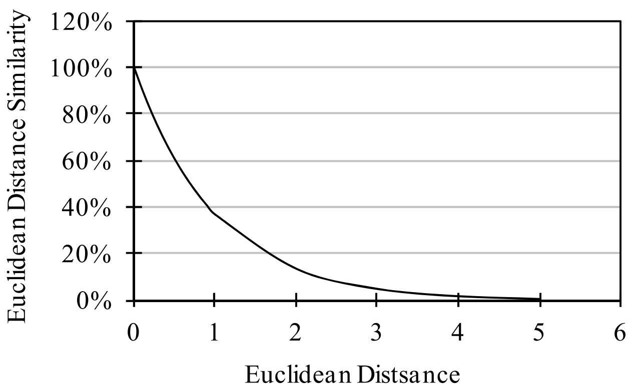

Fig.10 Euclidean distance similarity versus Euclidean distance

6. CONCLUSIONS

Two approaches called the cosine similarity method and the Euclidean distance similarity method proposed to diagnose abnormal whole building cooling or heating energy consumption faults are described in this paper. In these two approaches, a reference control change library collection of known whole building faults is determined in advance. The cosine similarity/Euclidean distance similarity within the observed fault signature vectors and reference control change signature vectors are calculated. Larger similarity values suggest a higher probability that the corresponding reference control change is the cause of the observed fault.

The proposed approaches were used to investigate the reasons for two abnormal energy consumption faults in two real buildings. In the two field test cases, the fault diagnosis results for both the cosine similarity and the Euclidean distance similarity method match the field survey results. This suggests that the cosine similarity method and the Euclidean distance similarity method are promising techniques for whole building fault diagnosis.

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Estimation of Building Parameters Using Simplified Energy Balance Model and Metered Whole Building Energy Use

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Abstract:
This paper presents and evaluates an indirect data-driven method to estimate influential building parameters: air exchange rates and overall heat transfer coefficients of building envelopes from the separately metered energy use for electricity, cooling and heating and weather data using multiple linear regression models based on the simplified steady-state energy balance for a whole building. Two approaches using different response variables: the energy balance load (E_{BL}) and the building thermal load (Q_B) and the use of monthly and daily interval data are evaluated using the synthetic data and the measured data from three large dormitory buildings. Although this method is not expected to replace actual measurement, easy and fast access to the influential building parameters allows new applications such as in preliminary investigation for energy conservation projects.

Keywords:
energy data analysis, parameter identification, data-driven models, energy balance

1. Introduction

Air exchange rates and overall heat loss coefficient of the building envelope have significant influences on the heating and cooling loads, but direct measurement of these parameters for a whole building scale in operating buildings requires considerable time and labor. This paper presents an indirect data-driven method to estimate the building parameters for operating buildings without direct measurement.

In data-driven approaches, the parameters are statistically estimated based on the relationship between input and output data. To obtain parameter estimates that allow direct physical interpretation, one needs to formulate models based on physical principles such as energy balance. Transient or steady-state models can be chosen depending on the required resolution of the model prediction, available data period and intervals, etc. This paper focus on the steady-state models using daily or monthly interval data to minimize transient effects due to building thermal mass and to average out the variations of ventilation rate and internal loads in a day so that the parameters can be reasonably constant over the modeling period.

Earlier studies on steady-state building parameter estimations generally use heating or cooling energy consumption data as a response variable in the regression models. However, using these models, simultaneous cooling and heating commercial buildings can cause misleading parameter estimations (Rabl and Rialhe, 1992). For commercial buildings, Reddy et al. (1994) explored the method to infer basic building parameters using the variable called the building thermal load Q_B. The Q_B variable is calculated from the whole building cooling and heating energy use, and the mixed hot and cold air streams in the HVAC systems in the building will be canceled out. Deng (1997) has developed a data-driven method to estimate overall heat loss coefficient and ventilation parameter using the Q_B model, and tested it with synthetic data. The parameter estimates are found to be accurate when daily data over an entire year are used, and biases due to multicolinearity—correlations between explanatory variables can be minimized using the estimation technique they developed, so called multi-step linear regressions. Another variable called the energy balance load E_{BL} has been proposed by Shao and Claridge (2006) as a part of energy data screening. The E_{BL} variable is similar to Q_B, but it includes the heat load from the electrical energy use. The E_{BL} variables plotted as a function of the outside air temperature shows a linear pattern that is unique to each building and faulty data can be detected as outliers visually or statistically using empirical models (Baltazar et al. 2007 and 2012).

In this paper, the method to estimate building parameters using the E_{BL} variable will be presented along with the method using the Q_B variable, and the estimation results are compared. Synthetic data from a computer simulation are used to evaluate the estimation, and to assess the application of the method to actual buildings, comparisons of measured outside air flow rates and the estimated values are presented. The use of newly introduced reference parameter T_{in}^* is discussed to alert unreliable parameter estimations.

Expected uses of the estimated parameters include: preliminary information for initial investigations in building energy optimization projects, reference input values in building energy simulations for existing buildings as a supplement to calibration procedures such as Claridge et al. (2003), and detection of operational changes with continuous monitoring. The automated application of the method as a part of energy information systems may be suitable for the facilities that require monitoring of large amount of buildings at the same time such as college campuses.

2. Formulation of models

2.1. Definition of E_{BL} and Q_B

Unified mathematical expressions for the parameters of the models using E_{BL} and Q_B variables are presented first. A system including the entire building is chosen as a control volume, and the boundary is set right outside the building exterior surfaces. The net change in the total energy of the control volume ΔE_{CV} is equal to the difference between the total energy entering and leaving the system. That is,

$$\begin{aligned}\Delta E_{CV} &= E_{entering} - E_{leaving} \\ &= Q_{air} + Q_{cond} + Q_{sol} + Q_{occ} + Q_E - E_C + E_H \end{aligned} \tag{1}$$

where Q_{air}, Q_{cond}, Q_{sol}, Q_{occ}, and Q_E are building heat load components from air exchange, conduction through exterior surfaces, solar insolation, occupants, and electricity energy consumed in the building, respectively. E_C, and E_H are separately metered whole building energy use of cooling and heating. When the time scale under study is long enough to diminish the thermal lag effect and the indoor air thermal condition is maintained constant, the system can be considered as a quasi-steady state, and the left hand side of Eq. (1) yields zero. The energy balance load E_{BL} is defined as (Shao, 2006):

$$
\begin{aligned}
E_{BL} &= Q_E - E_C + E_H \\
&= fE_E - E_C + E_H \\
&= -Q_{air} - Q_{cond} - Q_{sol} - Q_{occc}
\end{aligned} \tag{2}
$$

where E_E is the metered whole-building non-cooling electricity use. The multiplicative factor f represents a fraction of E_E which turns into the heat load ($0 \le f \le 1$). The factor f is not measurable but presumed to be fairly high. In practice, the available whole building level of electricity consumption is used for Q_E to calculate E_{BL}. In this case, Eq. (2) is re-written as:

$$
\begin{aligned}
E_{BL} &= E_E - E_C + E_H \\
&= -Q_{air} - Q_{cond} - Q_{sol} - Q_{occ} + (1-f)E_E.
\end{aligned} \tag{3}
$$

The electricity energy use which does not turn into the space heat load may increase the E_{BL}. Meanwhile, the building thermal load Q_B is defined as (Reddy et. al. 1994):

$$
\begin{aligned}
Q_B &= E_C - E_H \\
&= Q_{air} + Q_{cond} + Q_{sol} + Q_{occ} + Q_E \\
&= Q_{air} + Q_{cond} + Q_{sol} + Q_{occ} + fE_E.
\end{aligned} \tag{4}
$$

Deng (1997) and Reddy et al. (1999) introduced two multiplicative correction factors: k_s and k_l. The k_s is a fraction of internal sensible loads to measured electricity use of lights and equipment E_{LE} and the k_l is a fraction of internal latent load to the total internal sensible load which appears only when latent load exists. If all the internal loads are from the occupants and lights and equipment, this relationship is written as

$$
Q_{occ} + fE_E = E_{LE} k_s (1 + k_l X) \tag{5}
$$

where the indicator variable X is 1 when the latent load exists ($W_{oa} > W_{in}$) and 0 otherwise. Then the expression of Q_B becomes

$$
Q_B = Q_{air} + Q_{cond} + Q_{sol} + E_{LE} k_s (1 + k_l X). \tag{6}
$$

2.2. Key parameters

The problem will be simplified as the same manner as in Reddy et al. (1994 and 1999), Deng (1997), and Shao (2006). The assumptions for the simplified E_{BL} and Q_B models using daily or monthly resolution data can be summarized as follows.

1. Indoor air temperature T_{in} is constant.
2. Indoor humidity W_{in} does not exceed 0.01 kg/kg. No humidification is applied.
3. Overall heat loss coefficient and air exchange rate are constant.
4. No economizer or heat recovery device is used.
5. Building total solar load can be expressed as a linear function of the outside air temperature T_{oa}.
6. Occupancy load is overall constant.
7. Transient effect is negligible.

Based on these assumptions, Q_{air}, Q_{cond}, and Q_{sol} are expressed in the simplified steady-state load models as presented in Eq. (7), (8), and (9).

$$Q_{air} = m_v c_p (T_{oa} - T_{in}) + m_v h_v X (W_{oa} - W_{in}) \tag{7}$$

$$Q_{cond} = UA_s (T_{oa} - T_{in}) \tag{8}$$

$$\begin{aligned} Q_{sol} &= a_{sol} + b_{sol} T_{oa} \\ &= a'_{sol} + b_{sol} (T_{oa} - T_{in}) \end{aligned} \tag{9}$$

where a and b are constants. W_{in} = 0.01 kg/kg and the indicator variable X is 1 when (W_{oa}>W_{in}) and 0 otherwise. By inserting these into Equations (3) and (6), the multiple linear regression models for E_{BL} and Q_B are derived as

$$E_{BL} = \beta_0 + \beta_T T_{oa} + \beta_W X (W_{oa} - W_{in}) + \varepsilon \tag{10}$$

$$Q_B = \beta_0 + \beta_{sens} E_{LE} + \beta_{lat} X E_{LE} + \beta_T T_{oa} + \beta_W X (W_{oa} - W_{in}) + \varepsilon \tag{11}$$

where ε is a random error. The mathematical expressions for each regression parameter are presented in Table 1.

Table 1: Mathematical expressions for regression model parameters

Regression parameter	$\boldsymbol{E_{BL}}$	$\boldsymbol{Q_B}$
β_0	$(UA_s + m_v c_p + b_{sol})T_{in} - Q_{occ}$ $-a'_{sol} + (1-f)E_E$	$-(UA_s + m_v c_p + b_{sol})T_{in} + a'_{sol}$
β_T	$-(UA_s + m_v c_p + b_{sol})$	$UA_s + m_v c_p + b_{sol}$
β_W	$-m_v h_v$	$m_v h_v$
β_{sens}	Not available	k_s
β_{lat}	Not available	$k_s k_l$

From these expressions, the building parameters and the uncertainties are deduced as in Table 2. The overall heat loss coefficient estimated from the regression models cannot separate out the solar effect. To differentiate it from the U for the temperature difference between indoor and outdoor air, we use U^* which is defined as U^*A_s=UA_s+b_{sol}. The variable T^*_{in} is introduced as a reference parameter which is associated with the indoor air temperature T_{in} and resembles the balance point temperature (ASHRAE 2009). The physical interpretation of this parameter changes depending on the explanatory variables included in the regression model, which will be discussed later along with the estimation results.

3. Data and procedures

3.1. Synthetic data

The commercial reference building model for existing large office buildings constructed in or after 1980 in the climate zone with the representative city of Houston, TX (DOE 2010) is used to generate synthetic data using EnergyPlus simulation software. The building has 12 stories above ground and a basement, and the total conditioned area of 46,320.38 m^2 (498,588 ft^2). Each above-grade floor has 5 zones: north, east, south, and west perimeters, core, and plenum. Each floor has a single duct VAV system with reheat terminals, and the building does not use economizer.

Table 2: Equations to calculate building parameters and the uncertainties from the regression estimates and standard errors

Building parameter	E_{BL}	Q_B	Uncertainty
m_v	$-\hat{\beta}_W / h_v$	$\hat{\beta}_W / h_v$	$\Delta\hat{\beta}_W / h_v$
$U^* A_s$	$-\hat{\beta}_T + \hat{\beta}_W c_p / h_v$	$\hat{\beta}_T - \hat{\beta}_W c_p / h_v$	$\sqrt{(\Delta\hat{\beta}_T)^2 + (\Delta(\hat{\beta}_W \cdot c_p / h_v))^2}$
T_{in}^*	$-\hat{\beta}_0 / \hat{\beta}_T$	$-\hat{\beta}_0 / \hat{\beta}_T$	$\left(\frac{\hat{\beta}_0}{\hat{\beta}_T}\right)\sqrt{\left(\frac{\Delta\hat{\beta}_0}{\hat{\beta}_0}\right)^2 + \left(\frac{\Delta\hat{\beta}_T}{\hat{\beta}_T}\right)^2}$
k_s	Not available	$\hat{\beta}_{sens}$	$\Delta\hat{\beta}_{sens}$
k_l	Not available	$\hat{\beta}_{lat} / \hat{\beta}_{sens}$	$\left(\frac{\hat{\beta}_{lat}}{\hat{\beta}_{sens}}\right)\sqrt{\left(\frac{\Delta\hat{\beta}_{lat}}{\hat{\beta}_{lat}}\right)^2 + \left(\frac{\Delta\hat{\beta}_{sens}}{\hat{\beta}_{sens}}\right)^2}$

Note: the delta means the standard error

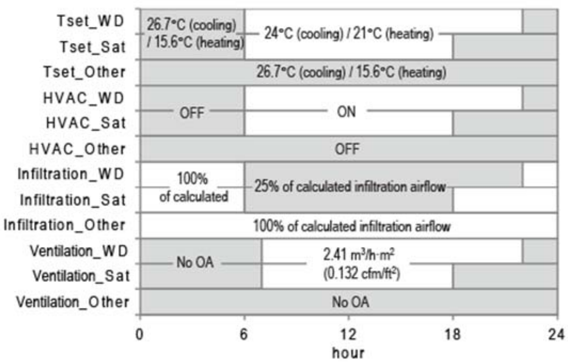

Fig. 1. System schedules for the as-is case

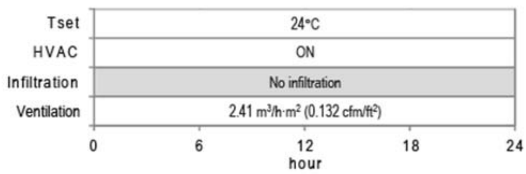

Fig. 2. System schedules for the ideal cases

Building operation in the original input file has three schedule patterns for weekday (WD), Saturday (Sat), and Sunday and holidays (Other) as shown in Fig. 1. During unoccupied hours, the HVAC systems are turned off until the zone temperatures exceed the set point temperatures; different set points are defined for cooling or heating and occupied or unoccupied hours. Another input file was prepared by modifying the schedules as in Fig. 2 to generate ideal data for parameter identifications. Then, the three sets of synthetic data were generated as in Table 3. Figure 3 shows the daily energy uses for electricity (lights, equipment, and fans), cooling, and heating, and Fig. 4 shows the E_{BL} and Q_B variables evaluated from these energy uses plotted versus the daily average temperature for the as-is case. Note that the signs of the Q_B plots are switched for the ease of visual comparison. Figures 5 and 6 show the same plots for the ideal w/o solar case.

Table 3: Measured values of outside air flow rates and energy data periods of E_{BL} and Q_B for three dormitory buildings

Case designation	**System schedules**	**Weather data**
As is	Fig. 1	TMY2 for Houston, TX
Ideal w/ solar	Fig. 2	TMY2 for Houston, TX
Ideal w/o solar	Fig. 2	Modified Houston TMY2 (solar insolation = 0)

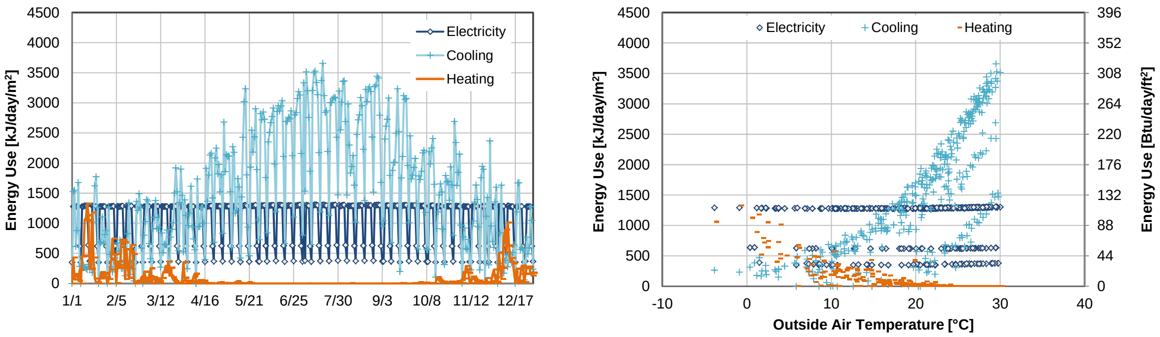

Fig. 3. Whole building daily energy uses for electricity, cooling, and heating per unit conditioned floor area for the as-is case. Time series plot is in the left and scatter plot versus daily average outside air temperature is in the right.

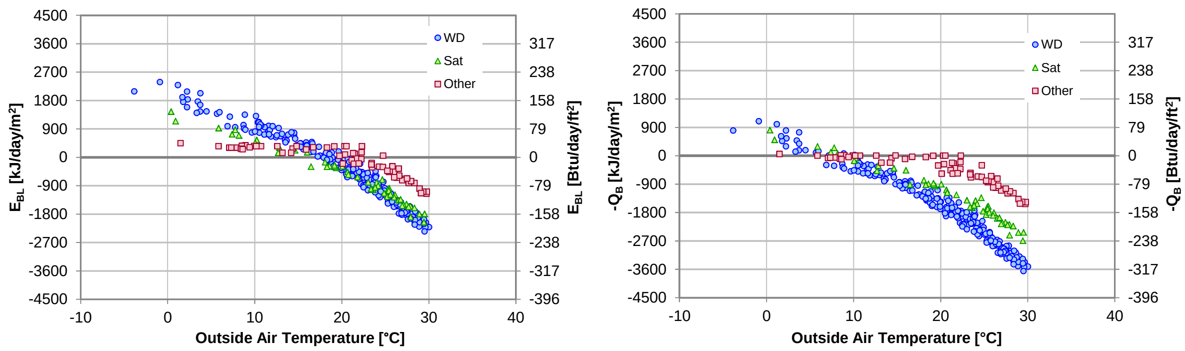

Fig. 4. E_{BL} and Q_B per unit conditioned floor area in the as-is case plotted versus daily average outside air temperature

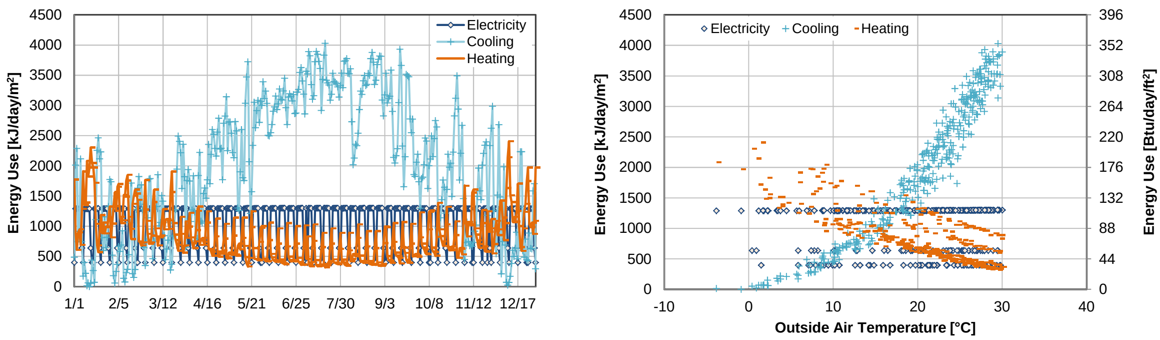

Fig. 5. Whole building daily energy uses for electricity, cooling, and heating per unit conditioned floor area for the ideal w/o solar case. Time series plot is in the left and scatter plot versus daily average outside air temperature is in the right.

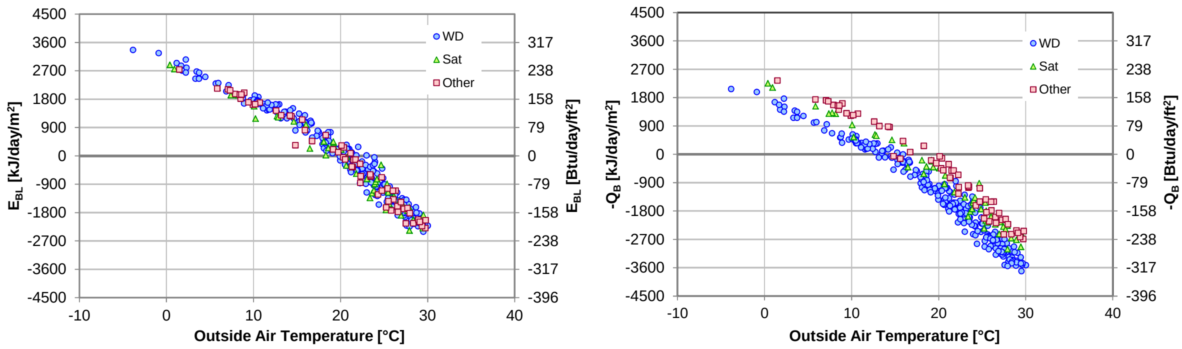

Fig. 6. E_{BL} and Q_B per unit conditioned floor area in the ideal w/o solar case plotted versus daily average outside air temperature.

3.2. Data from actual buildings

The whole building electricity, chilled water, and heating hot water energy use data are collected from the three dormitory buildings which have dedicated outdoor air systems (DOAS). The HVAC systems are operated continuously in these buildings. The outside air temperature and humidity ratio are obtained and calculated from the quality controlled local climatological data (QCLCD) for College Station, TX (NCDC 2012). The outside air flow rate has been measured at the OAHUs on 4/24/2012. The measured values of the building total outside air flow rate and the basic information on the available E_{BL} and Q_B data for these buildings are given in Table 4.

Table 4: Measured values of outside air flow rates and energy data periods of E_{BL} and Q_B for three dormitory buildings

Bldg Symbol	Gross floor area	Measured outside air flow rate on 4/24/2012	E_{BL} and Q_B data		
			Available energy use data period	No. of daily observations	No. of monthly observations
HS	69668 ft^2 (6472.4 m^2)	8779 cfm (14916 m^3/h)	7/1/2011–6/30/2012	320	12
MF	62156 ft^2 (5774.5 m^2)	10025 cfm (17033 m^3/h)	9/1/2011–6/30/2012	267	10
HB	62156 ft^2 (5774.5 m^2)	7750 cfm (13167 m^3/h)	7/21/2011–6/30/2012	329	12

3.3. Estimation procedure

Total of 14 sets of data listed in Table 5 were prepared, and the E_{BL} and Q_B variables were calculated for the each set. The data for the as-is case were grouped into three day types, because the parameters vary between those. The models have been estimated with the statistics software R (R Core Team, 2011). The electricity use variable E_{LE} is not included in the daily interval Q_B models for the separated as-is cases, because the daily electricity use for lights and equipment from the simulation is perfectly constant in the each day-type data, and the parameter estimates becomes zero. The variable XE_{LE} has been removed from the daily Q_B models for the three dormitories and from all the monthly Q_B models, because, when included, the direction of the effects becomes opposite from the physical response and/or the estimates are not statistically significant. The explanatory variable terms included in each final model are given in Table 5.

To detect the level of multicolinearity, the Variance Inflation Factors (VIF) have been calculated for each data set. The VIF is defined as:

$$\mathrm{VIF} = \frac{1}{1 - \mathrm{R}_\mathrm{i}^2} \tag{12}$$

where $\mathrm{R_i}^2$ is the multiple coefficient of determination between the *i*-th explanatory variable and all of the other explanatory variables in the regression equation. The exact value of VIF at which muticolinearity is declared depends on the individual investigator. Some use a value of 5 and others 10 (Haan, 2002).

Table 5: Data sets used in the analysis and the explanatory variable terms included in the regression models. The checked terms are included.

Dataset	Explanatory variable terms included in the regression models					
	E_{BL}		Q_B			
	T_{oa}	$X(W_{oa}\text{-}W_{in})$	T_{oa}	$X(W_{oa}\text{-}W_{in})$	E_{LE}	XE_{LE}
Daily interval						
Ideal w/ solar	✓	✓	✓	✓	✓	✓
Ideal w/o solar	✓	✓	✓	✓	✓	✓
As is (WD)	✓	✓	✓	✓		
As is (Sat)	✓	✓	✓	✓		
As is (Other)	✓	✓	✓	✓		
HS (Jul–Jun)	✓	✓	✓	✓	✓	
MF	✓	✓	✓	✓	✓	
HB	✓	✓	✓	✓	✓	
Monthly interval						
Ideal w/ solar	✓	✓	✓	✓	✓	
Ideal w/o solar	✓	✓	✓	✓	✓	
As is	✓	✓	✓	✓	✓	
HS (Jul–Jun)	✓	✓	✓	✓	✓	
MF	✓	✓	✓	✓	✓	
HB	✓	✓	✓	✓	✓	

4. Results and Discussions

4.1. Evaluation using Synthetic Data

The air exchange rates m_v converted into volumetric flow rate, overall heat loss coefficients U^* estimated from the daily interval synthetic data are compared to the assumed true values in Fig. 7. The estimates for the temperature parameter β_T are also presented for reference. The signs of the β_T estimates for E_{BL} and Q_B models are opposite, and the absolute values $|\beta_T|$ are used for comparison.

Overall, E_{BL} and Q_B models have consistent parameter estimates for the daily interval synthetic data sets. In the ideal cases, despite the solar insolation effect, the m_v is estimated reasonably accurate within 10%. The solar insolation increased the $|\beta_T|$ estimates by 9.1% (Q_B) and 6.8% (E_B) and decreased the m_v estimates by 6.8% (Q_B) and 7.9% (E_B), which directly resulted in the overestimation of U^*. It should be reminded that the true value of the overall heat loss coefficient in Fig. 7 is for U which does not include solar effect and smaller than U^*, and the overestimation includes this difference.

For the WD and Sat day types in the as-is case, the parameters are estimated fairly well and comparable to the ideal cases, nevertheless these simulation models have some exceptions from the model assumptions. The $|\beta_T|$ estimates in the WD and Sat day types are seemingly as good as in the ideal cases, however, we should be cautious of this result. The T_{in} decreases with the T_{oa} in the as-is case because of the set point and system operation schedules, which may decrease the $|\beta_T|$ estimate. But the $|\beta_T|$ estimate may be already overestimated as discussed earlier. These two factors may balance out to lead a pseudo-good estimation. This type of errors can be avoided by using variable (T_{oa}-T_{in}) instead of using T_{oa} or by correcting the model using a linear expression of T_{in} as a function of T_{oa}. For the Other day type, meaningful estimates are not available.

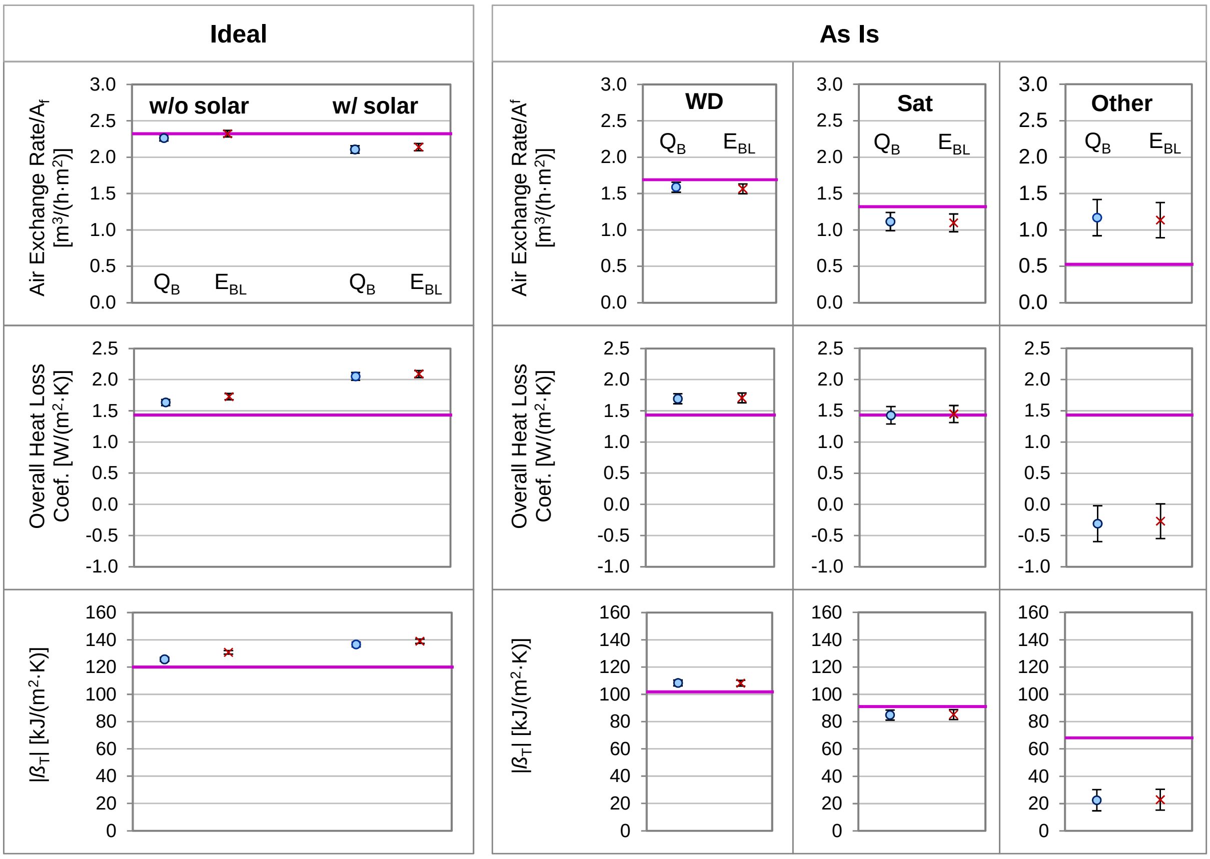

Fig. 7. Parameter estimates from synthetic daily data for the ideal and as-is cases. For each of three parameters, the assumed true value is shown as a solid line, and the parameter estimates using Q_B and E_{BL} are shown as a circle and a cross, respectively, along with the standard errors shown as bars.

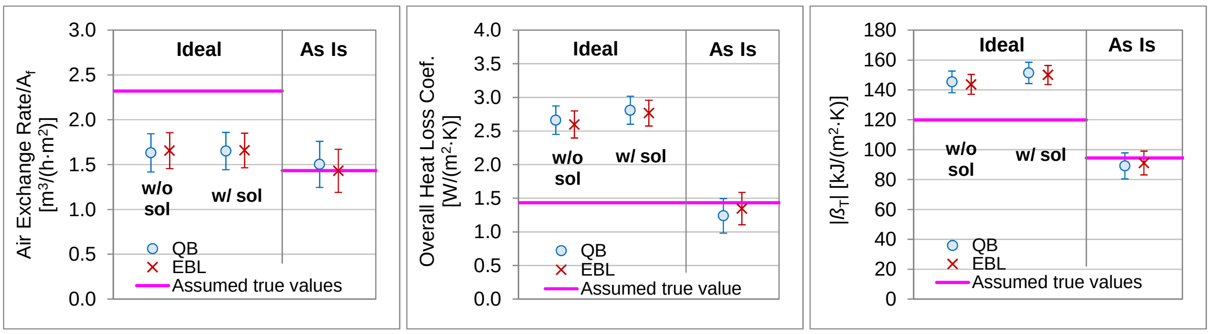

Fig. 8. Parameter estimates from synthetic monthly data for the ideal and as-is cases. For each of the parameters, the assumed true value is shown as a solid line, and the parameter estimates using Q_B and E_{BL} are shown as a circle and a cross, respectively, along with the standard errors shown as bars.

The parameter estimates using monthly interval data are presented in Fig. 8. In the ideal cases using monthly interval data, the estimated parameters have larger biases compared to the results from the daily interval data. This may be due to the large collinearity between the outside air temperature and humidity ratio variables in the monthly data, as the VIFs in **Error! Reference source not found.** shows large increase of the collinearity between T_{oa} and $X(W_{oa}\text{-}W_{in})$ in the monthly interval data. This indicates the model using monthly data is not able to separate effects of T_{oa} and $X(W_{oa}\text{-}W_{in})$ well. The reason for the good agreements between the estimates and the assumed true values in the as-is case using monthly data is not clear.

The T_{in}^* estimates for the synthetic data sets are shown in Fig. 9 along with the distribution of the daily average indoor air temperatures in the building. The physical meaning of this parameter changes with the structure of the models which mathematical expressions and approximate values can be found in Table 6. Both E_{BL} and Q_B models have good estimations for T_{in}^* in the ideal cases. In the as-is case, the bias increases as the unconditioned hours increases. The T_{in}^* estimated from E_{BL} models appear to be more stable over the different data sets, around a few degrees below the T_{in} when the HVAC systems are on for at least 16 hours per day. Based on these features of the T_{in}^* estimates from E_{BL} models, it is possible to create a rule of thumb for checking the estimated models. For example, the T_{in}^* should be in the range between the indoor air temperature and 2°C to 3°C below it; If the T_{in}^* is far away from the range, the model may not be reliable due to any possible reasons such as metering errors, model misspecifications, building operation changes during the data period, etc.

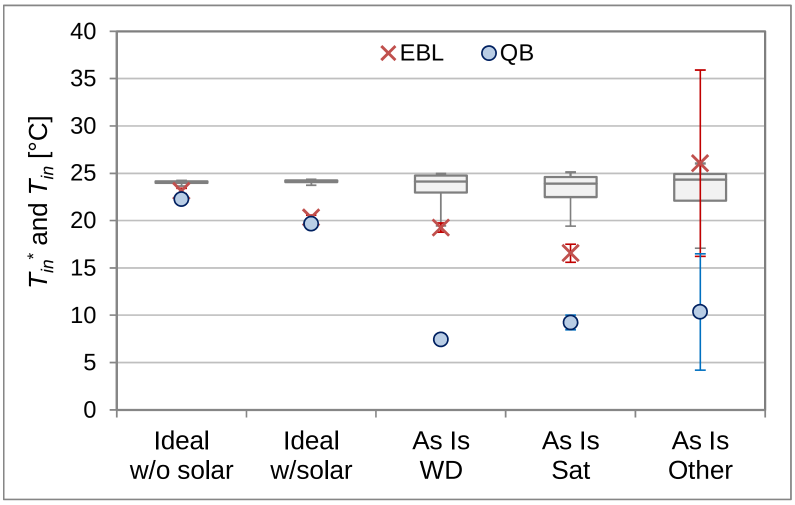

Fig. 9. Estimates of T_{in}^* and the distributions of T_{in}. For each case, estimates using E_{BL} and Q_B are shown with the standard errors, and the annual distribution of daily average T_{in} is presented by box and whisker plot.

Table 6. Physical meaning of the reference parameter T_{in}^* for different models used for synthetic data. Expected values are given.

Case	E_{BL}	Q_B
Ideal w/o sol	$T_{in} - \frac{Q_{occ}}{UA_s + m_v c_p} \sim 23.2°C$	$T_{in} \sim 24°C$
Ideal w/ sol	$T_{in} - \frac{Q_{occ} + a'_{sol}}{UA_s + m_v c_p + b_{sol}} \sim 21.8°C$	$T_{in} - \frac{a'_{sol}}{UA_s + m_v c_p + b_{sol}} \sim 22.6°C$
As is	$T_{in} - \frac{Q_{occ} + a'_{sol} - (1-f)E_E}{UA_s + m_v c_p + b_{sol}}$ $\sim 21.8°C$ if $f=1$	$T_{in} - \frac{Q_{occ} + a'_{sol} + fE_E}{UA_s + m_v c_p + b_{sol}}$ $\sim 13.8°C$ if $f=1$

4.2. Application to the Data from Actual Buildings

The air exchange rates estimated from the daily and monthly interval data from three dormitory buildings are compared to the measured values in Fig. 10, 16, and 17, and the VIFs of the variables are shown in Table 7. To see its effectiveness as a validation tool, the parameter T_{in}^* is also presented for each model. Overall, the estimates using daily data have similar values between Q_B and E_{BL} models for each building, but using monthly data, the estimates from E_{BL} models have better and stable results.

The proximity of the estimated parameters and the measured values vary between buildings. The HS building has the best estimations for the daily data, but it is underestimated for the monthly data, which is consistent with the results from the ideal cases of the simulation building. The T_{in}^* for the HS building falls in the expected range. The MF building has comparable results between daily and monthly data unlike other buildings. The VIFs of the monthly data for the building MF are small compared to the dataset for the other buildings, which should be due to lack of the data for July and August, the most hot and humid months. This less collinearity might be the reason for the similar results between the daily and monthly data.

Monthly data consist of small amount of data, and the estimates can be strongly influenced by anomalies. This seems to be the case with the building HB which appears to have changes in the outside air flow rate during the data period. The estimate from the monthly Q_B model for the HB building has about 140% higher than the measured value with a very low statistical significance. This seems to be caused by the collinearity between E_E and ($W_{oa}-W_{in}$), which can be seen in the high VIFs for these variables compared to the other datasets in Table 7. In fact, the effect of the E_E variable is overestimated around 5 times as the normal level. These abnormal estimates are alerted by the T_{in}^*; the estimate of T_{in}^* for the monthly Q_B model for the HB building is near 50°C which is not a realistic value based on the rule of thumb discussed earlier.

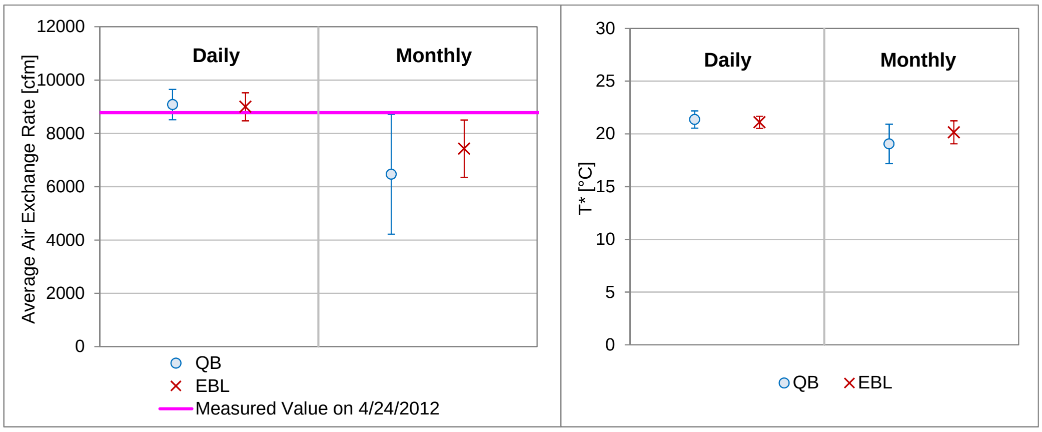

Fig. 10. Daily average outside air flow rate (left) and T_{in}^* (right) estimated for building HS comparing the estimates from daily and monthly interval data. Two different data periods are used. The standard error is shown with bars for each estimate. 1 cfm = 1.699 m^3/h.

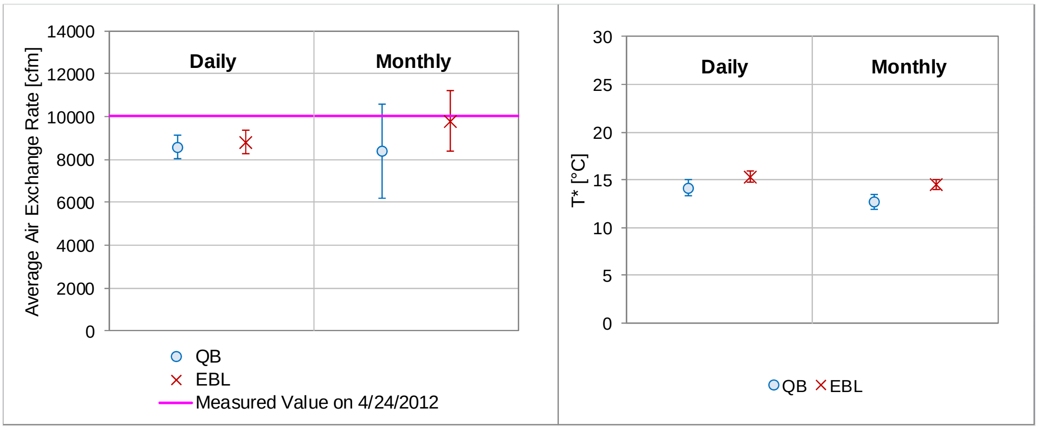

Fig. 11. Daily average outside air flow rate (left) and T_{in}^* (right) estimated for building MF comparing the estimates from daily and monthly interval data. The standard error is shown with bars for each estimate. 1 cfm = 1.699 m^3/h.

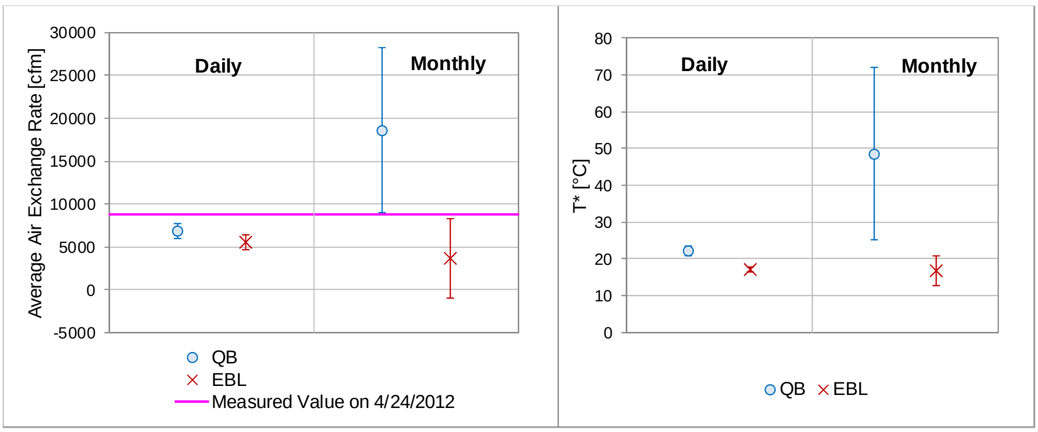

Fig. 12. Daily average outside air flow rate (left) and T_{in}^* (right) estimated for building HB comparing the estimates from daily and monthly interval data. The standard error is shown with bars for each estimate. 1 cfm = 1.699 m^3/h.

Table 7: VIFs for explanatory variables in the models for three dormitory buildings. For each set of variables, the values for daily and monthly data are compared.

Explanatory variable	HS				MF				HB			
	Daily	Monthly	Daily	Monthly	Daily	Monthly	Daily	Monthly	Daily	Monthly	Daily	Monthly
T_{oa}	2.95	14.53	2.86	4.25	2.17	5.23	2.13	2.48	2.72	11.39	2.66	4.01
$X(W_{oa}-W_{in})$	3.16	15.28	2.86	4.25	2.33	5.52	2.13	2.48	2.96	21.51	2.66	4.01
E_E	1.13	3.69			1.11	2.33			1.15	6.19		

5. Conclusions

The E_{BL} and Q_B models generally have a similar level of accuracy in the parameter estimation. However, the effects of the variables E_E and XE_E (i.e. k_s and k_l) in the Q_B models cannot be estimated properly in some cases and the inclusion of the variable may cause unexpected deviations in the parameter estimates, hence, Q_B models require more careful model selections compared to E_{BL} models. The estimations using daily data are fairly accurate when the HVAC systems are on for longer hours in the day. In the synthetic data for the commercial reference building model, meaningful estimates have been obtained for the schedules with the HVAC operation for 12 hours a day and longer (WD and Sat schedules). This indicates the method does not require a strict conformance to the constant parameter assumption, and the building without continuous HVAC operation can still be analyzed using this method by separating data into the day types with the same operation schedules. Meanwhile, the use of monthly data should be warned because of the large collinearity between the outside air temperature and humidity ratio and high sensitivity to the anomaly.

This method is applicable when the non-cooling electricity, cooling, and heating energy uses are metered separately. The method relies on the correct measurement; before the parameter estimation, one should check the validity of the data using appropriate techniques. It is often the case with the actual buildings that the building operations change during the modeling period. Such changes can be detected by analyzing the model residuals. The proposed reference parameter T_{in}^* may be used to detect some problems in the metered energy data and model misspecifications. The advantage of this parameter is the acceptable range is predictable without special knowledge of the building. The method to establish reasonable ranges for T_{in}^* under given conditions may be developed in the future study. The estimation of the outside air flow rate depends on the outdoor air humidity ratio variable, and if the data lacks hot and humid ambient conditions, the estimates may not be reliable. This can be caused by missing data but also resulted from the dry climate where the building stands. The applicability of the method to the different climate zones should be scrutinized.

6. Acknowledgements

Authors would like to thank *CC*® Team at Energy Systems Laboratory for the on-site measurements and useful information about the buildings. The monitored data used in this study was obtained from Texas A&M University Utilities & Energy Services Department, and we would like to thank all the personal for making the data available to us.

Nomenclature:

A_f = conditioned floor area of building, m^2
A_s = exterior surface area of building, m^2
c_p = specific heat at constant pressure, kJ/kg·K
E_{BL} = Energy balance loads, J
h_v = specific heat of vaporization, kJ/kg·K
k_l = ratio of internal latent loads to total internal sensible loads of building
k_s = multiplicative factor for converting Q_{LR} to total internal sensible loads
m_v = outside air exchange (ventilation) flow rate, kg/s
Q_B = Building thermal loads, J
E = metered energy use inside the building, J
T = dry-bulb temperature, °C
U = overall building envelope heat loss coefficient, $W/m^2 \cdot K$
W = humidity ratio, kg_w/kg_{da}
X = indicator variable
$ß$ = parameter of regression models

Subscripts:

E = whole building electricity
LE = whole building electricity (lights and equipment)
C = whole building cooling
H = whole building heating
oa = outside air
in = indoor air
sol = solar

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Supermarket Energy Retrofit

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Abstract:
Supermarkets use nationally significant quantities of energy with an average store exceeding 600 kWh/m2 pa.

The reason is simple. The design of these stores is to maximise sales and minimise initial costs. Energy costs are insignificant compared to the huge turnover generated, often less than 0.4%. If any energy conservation measure (ECM) has even a slight negative impact on sales, the savings for the storeowner will be wiped out.

Can an existing supermarket be retrofitted to substantially reduce energy consumption and maintain or increase sales?

This is the challenge that confronted us with our first supermarket energy retrofit and yes it can be done. We have achieved 36% energy savings and total sales for the store have increased 6% over the same period.

Keywords:

Lighting, Refrigeration, Retail, Skylights, Retrofit

1. Introduction

A conventionally built supermarket has a combination of features that result in excessive energy consumption. There are open refrigerated displays adjacent to occupied heated aisles and very high lighting levels, often without natural lighting and a single-minded focus on increased sales.

From an engineering point of view, a supermarket is inherently inefficient and uncomfortable with compromised product temperature control. Where else do you find -25°C maintained next to a 20°C aisle with no barrier but an air curtain?

These same issues mean that the potential for savings in supermarkets is huge. The savings we achieved in this project are only the beginning. We achieved 36% energy savings in a store which even now has 90% of the medium temperature cabinets without any doors. If we could get doors on all of those cabinets, we estimate 50 to 60% savings are possible, along with increased customer comfort and improved product temperature control.

The main barrier to achieving this is the perception (from store management) that doors on cabinets will reduce sales. Placing a barrier between the customer and the product is considered bad practise.

The reality of the introduction of doors is much more complex than this simple rule. Yes, in some situations, with some products, the sales may reduce but in others there will be no effect or even a positive effect on sales. Whether the product is a staple or discretionary, how cold it is in the aisle, where the cabinet is located within the store and even global economic conditions will all affect sales and it is often difficult to isolate these factors.

To successfully add doors on refrigerated cabinets, we must think outside the engineering involved and ensure the marketing, promotion and product display is improved. Use stickers on doors to tell the customer what is being achieved, ensure the product is clearly displayed and well lit and try to co-ordinate promotional activity around door installation to offset any potential negative effects.

Most supermarkets are in single storey big box retail buildings with great potential for natural lighting, especially if there is no suspended ceiling. In spite of this the vast majority of stores do not have adequately designed or fully integrated natural lighting. The stores that do have skylights are normally inadequate to fully illuminate the store and most do not have an automated control system to switch off the lights, so they run regardless of light levels in the store.

In our experience, good skylight design combined with an automated dimming control system will achieve substantial energy savings and improve the store environment significantly during the day. This project also proved the viability of retrofitting skylights in an operational store with little or no disruption to business.

There are many energy saving initiatives that can be implemented in supermarkets but the big two are natural lighting and doors on fridges. They are not the easiest to implement but they must be implemented effectively if substantial savings are to be achieved in supermarkets.

2. Food Retail – National Significance in New Zealand & Australia

The supermarket sector is the largest application of non-domestic refrigeration and consumes the best part of 4% of all electricity consumed in Australia and New Zealand. The technology is complex, capital intensive and has long life spans. There is a slow uptake of energy efficient systems, products and practices (Ellis, 2009).

The energy use of supermarkets is nationally significant and long life span of equipment and buildings means a retrofit solution is needed to reduce this consumption in the medium term.

The aim of this project is to provide a working example of the energy efficiency measures that can be implemented in a typical operational supermarket.

2.1. Site Description

The Pak'n Save store is located in the CBD of Whanganui, a small provincial town in NZ with a population of 43,000. The district enjoys a temperate climate with 2,100 average sunshine hours per annum and about 882 mm of annual rainfall. Several frosts are experienced in winter and the latitude of the town is 39.93°S.

Climate data for Whanganui													
Month	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**	**Year**
Average high °C (°F)	22.4 (72.3)	22.7 (72.9)	21.3 (70.3)	18.8 (65.8)	16 (61)	13.8 (56.8)	13.2 (55.8)	13.8 (56.8)	15.3 (59.5)	17 (63)	18.8 (65.8)	20.7 (69.3)	17.8 (64.0)
Average low °C (°F)	14 (57)	14 (57)	12.9 (55.2)	10.6 (51.1)	8.5 (47.3)	6.5 (43.7)	5.6 (42.1)	6.2 (43.2)	8 (46)	9.6 (49.3)	10.9 (51.6)	12.8 (55.0)	10 (50)
Rainfall mm (inches)	62 (2.44)	65 (2.56)	68 (2.68)	71 (2.8)	81 (3.19)	82 (3.23)	88 (3.46)	70 (2.76)	72 (2.83)	81 (3.19)	74 (2.91)	70 (2.76)	882 (34.72)
Source: NIWA Climate Data													

Fig. 1. Whanganui Climate Data

The store was purpose built as a supermarket in 2005 and is 6,400m² in size.

The mezzanine level is divided between the admin and the back of house, which includes the staff café, locker room, toilets and main plant-room.

The back of house area (BOH) contains the freezer rooms, cool rooms, bakery, butchery, general storage for all departments and the loading dock.

All plant is electric apart from some of the ovens in the bakery and the domestic hot water boiler, which use natural gas.

Common plant equipment and distribution boards (DBs) are located on the admin mezzanine, ground floor and BOH mezzanine. The main incoming DB board and meter are located in the main plant-room on the BOH mezzanine. Before the project was implemented there was no sub-meters installed on site.

The main food hall area is air conditioned by a single zone AHU with small heat pump units supplying other areas.

The store is occupied 23 hours a day 363 days a year and opening hours are from 7:00am to 10:00pm. The bakery runs between 3:00am and 12:00pm each day.

Customer numbers average around 23,000 per week.

3. Energy Consumption

3.1. Monthly Electricity Consumption

Figure 2 shows monthly electricity usage over a period of two and a half years from January 2010. The energy conservation measures (ECMs) implemented as part of this project took place between March and September of 2011 and reduced consumption considerably over this period.

The consumption figures from 2010 indicate the highest energy use is during the summer. This is due to increased refrigeration load with warmer ambient temperatures. Most of the store heating is recovered from the refrigeration system in the winter, which reduces demand in the colder months.

The post project energy consumption is much more consistent throughout the year without the high peak demands over the summer. This is because the natural lighting (skylights) provides increased savings during the longer summer days which offsets the increased refrigeration loads. Also the refrigeration ECMs reduced the load on the air cooled condenser racks and they can handle the peak summer loads with reduced head pressures.

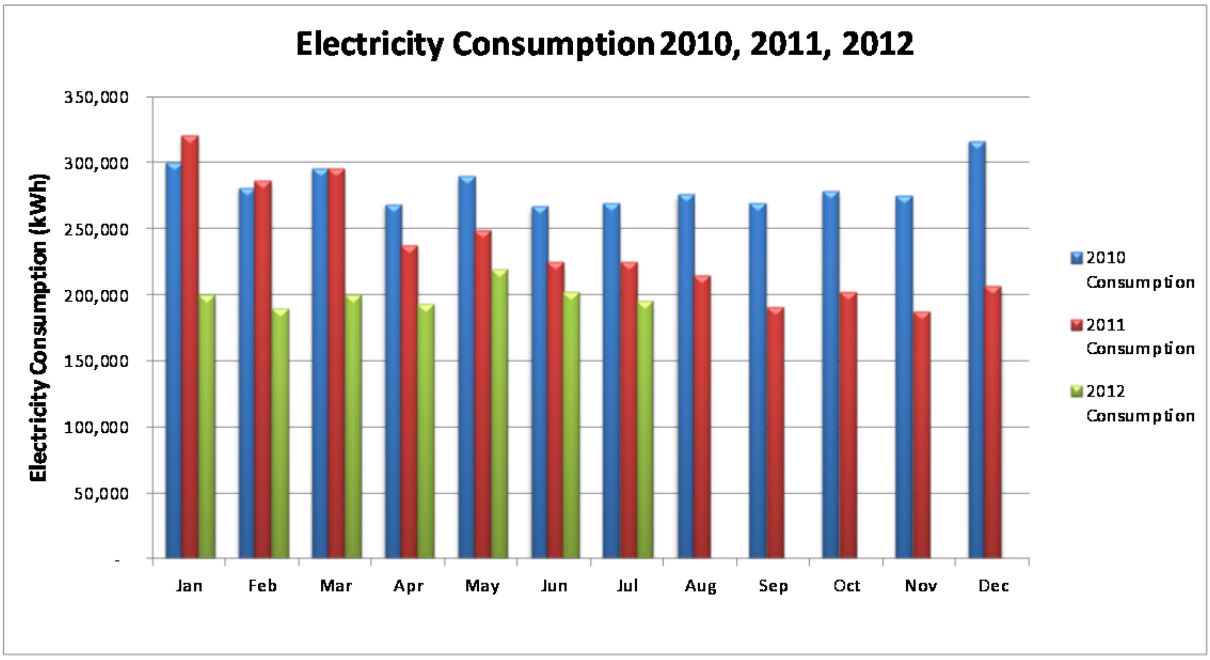

Fig. 2. Store Electricity Consumption (2010-2012)

The increase in energy consumption during May and June 2012 was due to a change in store operation. The night shelf stacking hours were increased and the staff were overriding the lights on all night. Analysis of the sub-meters showed the increase clearly and the lighting control was re-programmed to accommodate the operational changes and reduce energy consumption.

3.2. Daily Electricity Consumption

Figure 3 shows average daily electricity consumption profiles for each month in 2011. The change in these profiles over the year indicates the effect of the project on energy consumption.

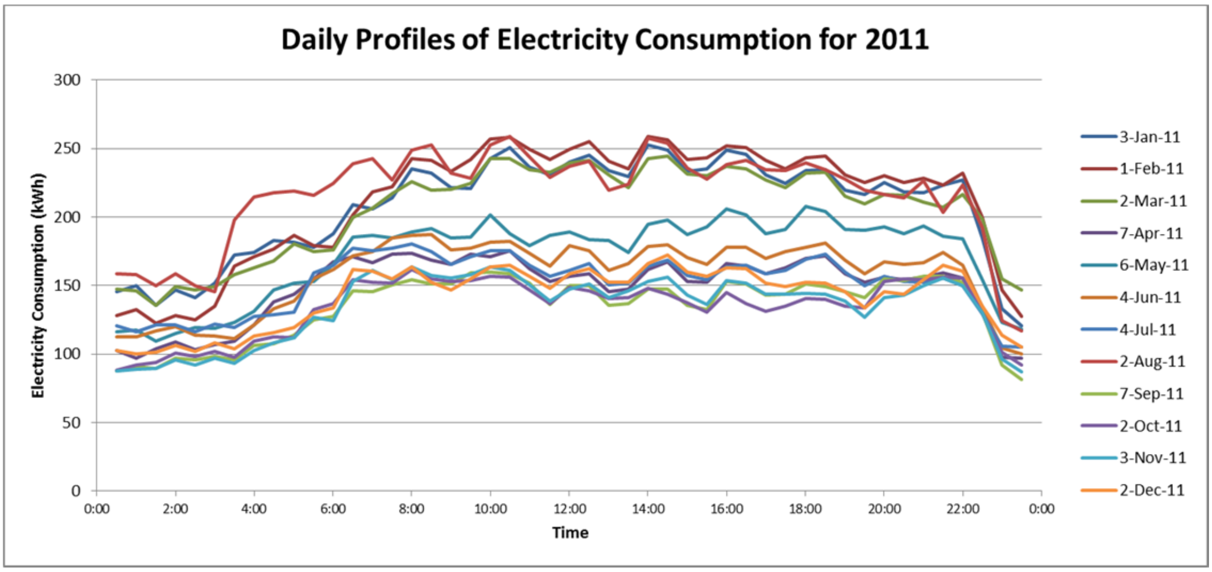

Fig. 3. Daily Electricity Consumption Profiles 2011

The initial increase in consumption for each day starts at approximately 3:30am with the arrival of the bakery staff. Consumption is then relatively consistent until about 6:30am as other staff arrive to begin their shifts. By 8:30am the store is at full load and runs consistently until 10:30pm when the store closes.

The energy savings generated by the project are very clear from these profiles. The peak consumption for the day has reduced by approximately 40% while the overnight base-load has reduced by around 33%. This again is because the savings made with natural lighting normally occur at peak load times during the day and the refrigeration load has been reduced.

3.3. Maximum Energy Demand

Figure 4 shows the peak monthly electricity demand for the store in 2011. Maximum demand is calculated on the amount of electricity (in kWh) consumed each half hour and the data is collected from the revenue meter on site.

As shown below, the electricity maximum demand for the site reduced considerably during 2011 due to the ECMs implemented. This has resulted in considerable savings on lines charges for the store owner, in addition to consumption savings.

The reduction in peak demand means further savings can be made by reducing the size of the on-site transformer. Currently the transformer is sized for 1000 kVA and we are now looking to reduce this to a 500 kVA unit.

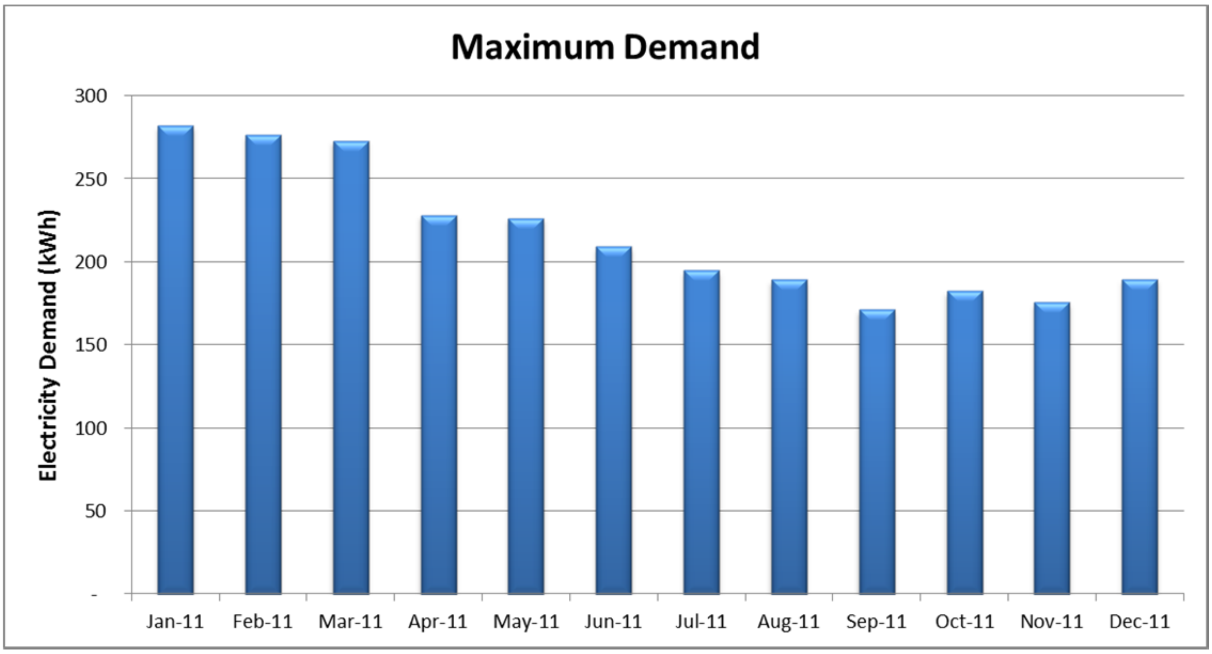

Fig. 4. Monthly Maximum ½ Hourly Electricity Demand 2011

4. Energy Balance

4.1. Pre-Project Energy Balance

Figure 5 shows the energy balance for the store before the project was implemented. The major loads are refrigeration, lighting and HVAC which use over 96% of the electricity consumption in the building.

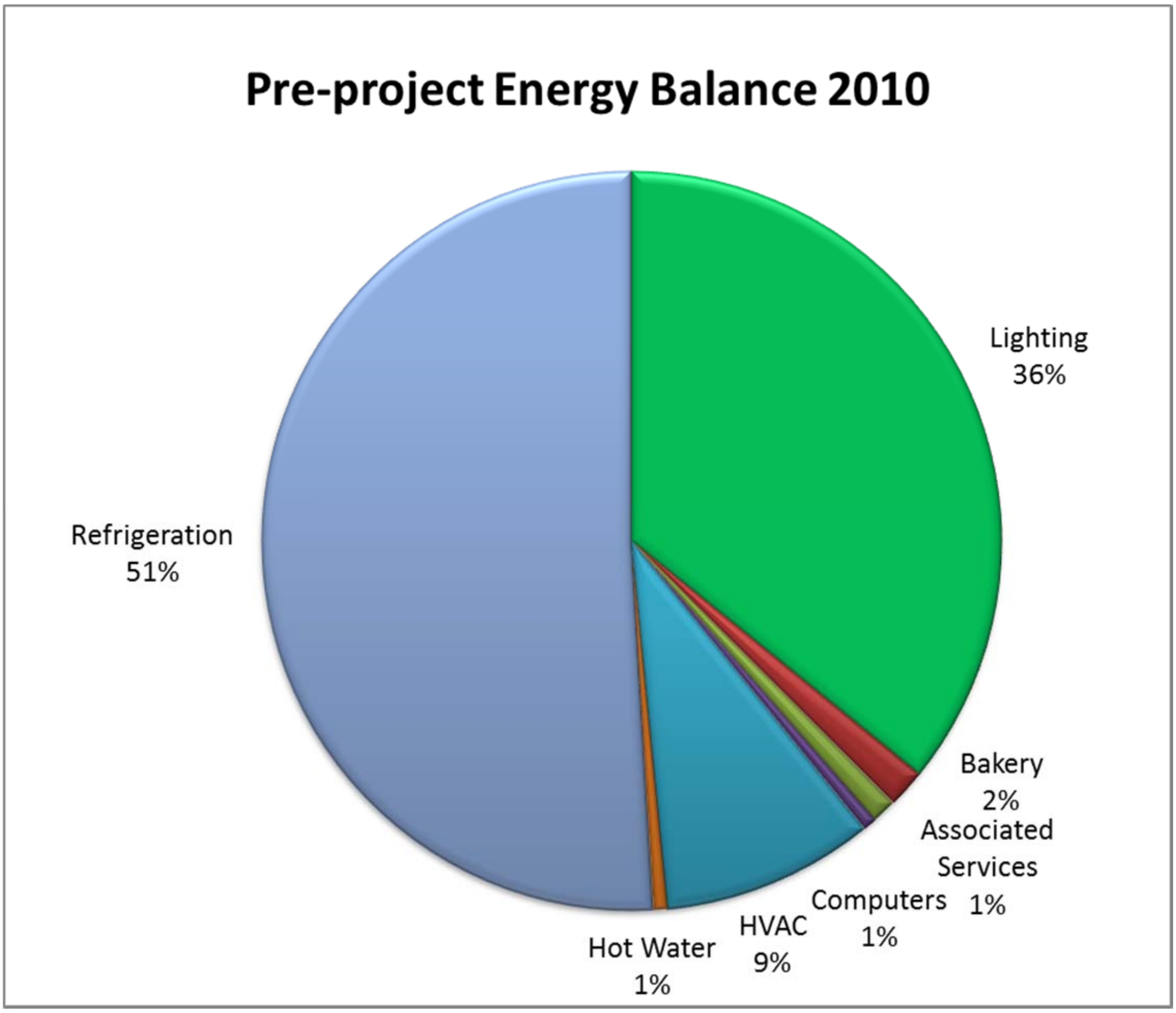

Fig. 5. Store Energy Balance (Electricity only)

We have not included the gas consumption for the store in the energy balance to maintain the focus on the significant energy savings achieved in electricity. The gas consumption (bakery ovens and domestic hot water) is included in calculations for the Energy Use Index (EUI) of the store.

4.2. Post-Project Energy Balance

The general proportions of the energy balance have remained reasonably stable during the project, although lighting has reduced from 36% to 33%. Significant savings were made in refrigeration, lighting and to a lesser extent HVAC but there is still more potential for refrigeration and lighting.

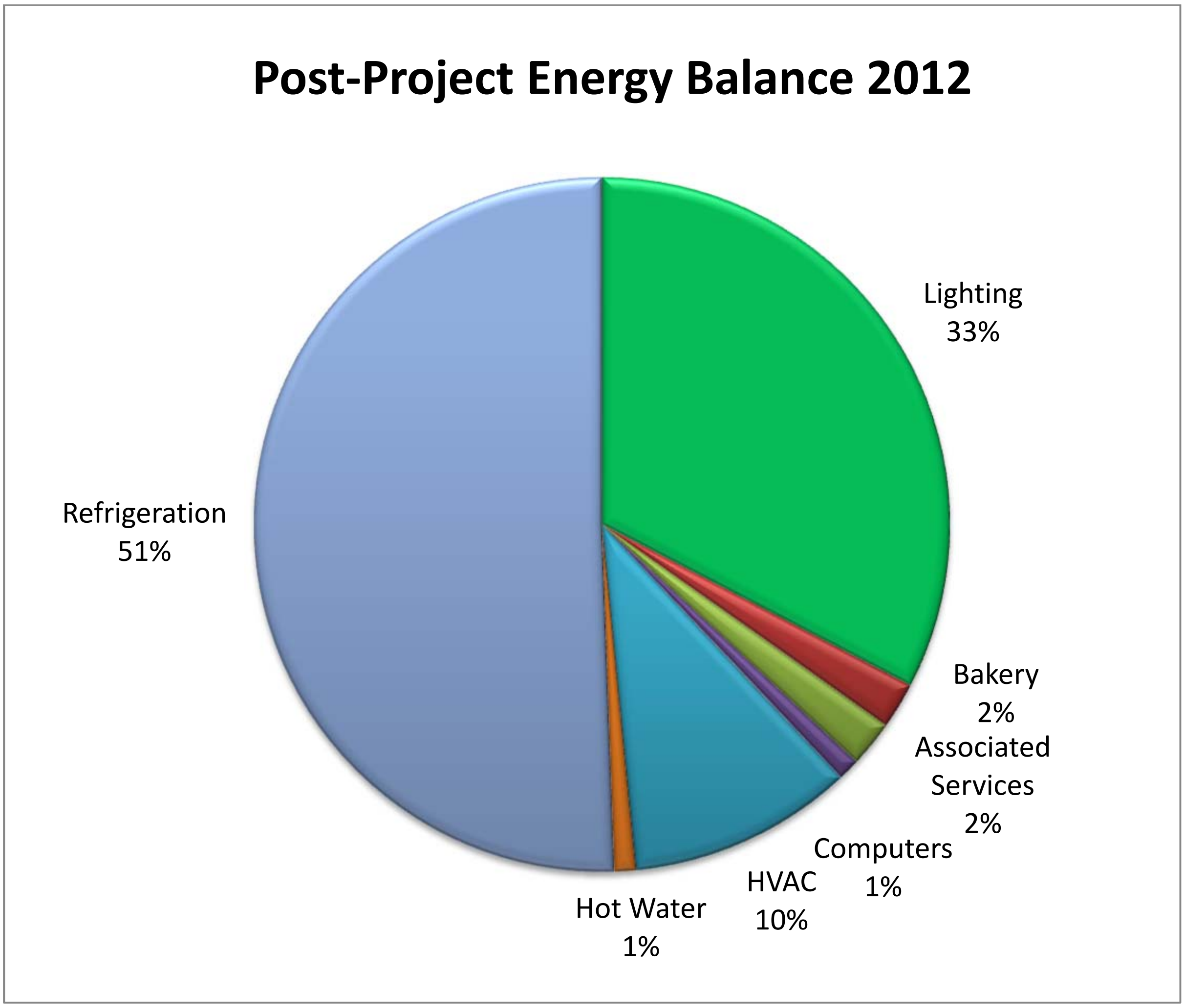

Fig. 6. Store Energy Balance (Electricity only)

5. Energy Benchmarks

5.1. Pre-Project Energy Benchmarks

The largest component of energy consumption for the store is refrigeration and special attention is needed to benchmark energy consumption in this area. The store contains cool rooms, freezer rooms and refrigerated displays served by a central refrigeration plant. The refrigerated displays are by far the largest load on the plant and the major focus for the retailer, so it makes sense to use them as an index for refrigeration energy use in the store.

We have developed an index or benchmark for the store that also enables comparisons with the Minimum Energy Performance Standards (MEPS) or High Energy Performance Standards developed by EECA (Energy Efficiency & Conservation Authority) here in New Zealand. EECA is a government agency working to improve energy efficiency and promote the use of renewable energy in New Zealand. http://www.eeca.govt.nz/

The MEPS and HEPS standards for Refrigerated Display Cabinets (RDCs) rate various types of displays based on the amount of energy used by 1 square meter of display in one day (24 hour period). We have used the same system to benchmark the refrigeration energy use in this store.

Table 1: Energy Index Table

	Building Area *(m^2)*	***Refrig. Display Area*** *(m^2)*	***Total Energy*** *(kWh/pa)*	***Refrig. Energy*** *(kWh/pa)*	***EUI*** *(kWh/m^2/pa)*	***RDI*** *(kWh/m^2/day)*
Pre-Project	6400	140	3,634,686	1,700,175	567.9	33.3
Post-Project	6400	144	2,651,970	1,228,941	414.4	23.4

The RDI has decreased by 30%, which is significant when you consider 90% of all the medium temperature cabinets are still without doors.

6. Lighting

6.1. Pre-Project Lighting

The lighting level in most areas was good and is often in excess of requirements. The entrance lobby is one area that was over lit, with levels of over 1100 Lux in recorded in some areas.

There was no use of natural daylight in the store, apart from the entrance lobby and car park ramp area. In each of these areas, the lighting did not reduce with increased daylight so no savings were achieved.

The main foodhall was lit with 400W metal halide fittings, which ran at 100% for 16 hours a day and were manually switched to 50% in the morning, when the bakery staff arrived. If staff switch the lights on and off as instructed, they will run the equivalent of 18 hours per day at 100%. In our experience, the only reliable way to ensure lights are switched off is to automate their operation. Staff cannot be relied upon to consistently switch equipment off at appropriate times together with their primary responsibilities.

The light levels recorded in the main aisles were between 580 and 840 Lux at 1m above floor level. The specified lighting level is 600 Lux. The variation in light level is due to variation in lamp age.

There was also significant lighting load within the refrigerated displays in the store. These are not counted with the official lighting load as they are considered part of the refrigeration plant. The cost to run these lights is increased because you pay for energy to run the lamp and for the refrigeration system to remove the heat produced by the lamp.

All of the refrigerated display lamps are fluorescent, which do not operate very well in the cold. This means an increased maintenance cost because the lamp life is reduced. Fluorescent lamps produce UV light which fades product and produces heat that can reduce product shelf life. We have observed many cases of over stacked shelves with product placed too close to the lights causing product overheating.

The lighting level recorded in these displays ranged from 500 to 2000 Lux.

There are many areas outside the main foodhall that are not occupied consistently and do not require lighting when unoccupied. Most are controlled with a manual wall switch. We have observed many lights still running when not needed and wasting energy.

The lighting in the covered car park is manually switched and often not needed. Often the occupancy in this car park is minimal.

6.2. Introduce Natural Lighting

A major focus of this project from the beginning was to add natural light into the store. The energy savings effects of this are obvious (the main foodhall lights switch off completely on bright days) but other softer benefits are also crucial.

The skylight installation without doubt had the biggest impact on customers and staff of any measure we introduced. The increased natural light had a feel good factor and common sense logic that did not need to be explained to customers. In essence, the skylights bring the natural world into the store. For a retailer trying to promote their credentials as environmentally friendly, nothing is a better fit than saving the global environment by improving the store environment.

The process of retrofitting skylights also increased the awareness of customers and staff to the improvements. The install took around six weeks and we began at one side of the store and worked our way across. As most customers are in the store at least once a week they could see the transformation as it progressed and noticed the difference between artificial and natural light.

A white paper prepared for the California Energy commission provides in-depth analysis of effects of daylight on retail sales. Their study of 73 California stores revealed benefits to sales, staff retention and showed that even customers who didn't notice the skylights, judged the store to be "cleaner" and "more spacious" (Heschong, 2003).

The following images illustrate the transformative effect skylights had in the store.

Fig. 7. Before & after skylight installation (note: lights are off in skylight photo)

6.3. Efficient Lighting Replacements

A variety of luminaires were replaced with more efficient options as part of this project. The major items are listed as follows:

- **Replace Main Foodhall Metal Halides with Dimmable Hi-Bay T5 Fluorescents**

  The original 400W (450W with Ballast) Hi-bays were replaced with T5 (4 x 54W) hi-bays which produce more light, better colour rendition, significant energy savings and are easily dimmed when daylight is available. The replacement fittings are 250W (Max.) and use considerably less when dimmed.

- **Replace Underground Car Park Lighting**

  The original twin 58W T8 Fluorescent fittings in the carpark were replaced with high efficiency twin 28W T5 luminaires with daylight control (in naturally lit areas) and occupancy control. When the car park is empty of people, the fluorescent lamps switch off and are replaced by small LEDs to provide minimal lighting. As soon as movement is sensed the fluorescents switch back on.

- **Replace Refrigeration Lighting**

  All of the fluorescent lighting in the refrigerated display cabinets, cool rooms and freezer rooms was replaced with LED tube fittings. The LEDs work well in the cold and offer significant savings for energy consumption, maintenance and improved light levels.

6.4. Improve Lighting Control

The existing lighting control in the store was a combination of individual time-clocks, daylight sensors and manual controls. Many of the time-clocks were overridden or incorrectly set up and often manually controlled items were simply left running 24/7.

As part of the project we installed a fully programmable lighting control system to replace the existing time-clocks and provide flexible and fully integrated dimming control of the main foodhall lighting.

The hi-bay fluorescents are dimmed in separate zones to provide consistent light levels in all areas regardless of the natural light available through the skylights. In addition, the lamps dim outside store opening hours while staff stack shelves, to achieve further savings.

The key to achieving savings in the retail areas is seamless control. If banks of light are switched or the dimming control is too rapid, the occupants notice the change and attention is drawn to the lighting operation. The light levels in the store can change quite quickly on days with wind and scattered cloud (common in NZ) so a compromise must be struck between speed of operation and gradual dimming control. In our experience, accurate dimming control is crucial to provide a useable solution with skylights.

7. Refrigeration

7.1. Pre-Project Refrigeration

The system is well maintained with very comprehensive controls but many of the display cabinets are inefficient.

Condenser heat is used to pre-heat the domestic hot water (DHW) and provide all the space heating in the main retail area, even on the coldest days of the year.

The lead compressor on the low and medium temp racks did not have variable frequency drives (VFDs).

Fig. 8. An infrared image showing cold aisle conditions for customers

Many of the aisles with open displays are noticeably cold. This is not only uncomfortable for shoppers, but indicates inefficient operation. This has been observed even when displays were not over stacked and seems to be inherent with the open vertical display cabinets.

7.2. Post-Retrofit Refrigeration

The open refrigerated display cabinets represent a large part of the refrigeration load. The obvious answer is to use glass door displays instead of open refrigerated displays but it may be difficult to convince the store management.

Fig. 9. Double glazed doors were retrofitted onto the beer and wine cases

A glass door display is always going to separate the cold and warm air better than an open display and should be used when possible.

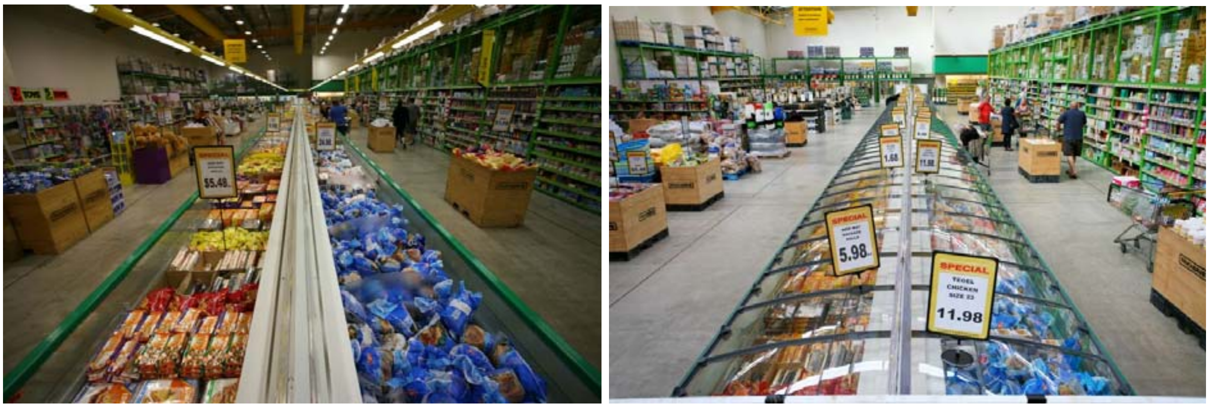

Fig. 10. Lids and EC Fans were retrofitted into existing chest freezer cases

An effort must be made to stop displays being over stocked. This is quite common and causes increased losses from the refrigerated cabinets and often increased product temperatures. Staff education and small changes to cabinet design can make all the difference.

We installed VFDs on the lead compressors of the low temp and medium temp racks to provide more accurate capacity and suction pressure control.

All of the condenser fans were replaced with electronically commutated (EC) fans with integrated speed control. Instead of switching on/off fans to control head pressure, all the fans ramp up and down together on to a single speed. This means fan energy is saved and the head pressure of the system is better controlled.

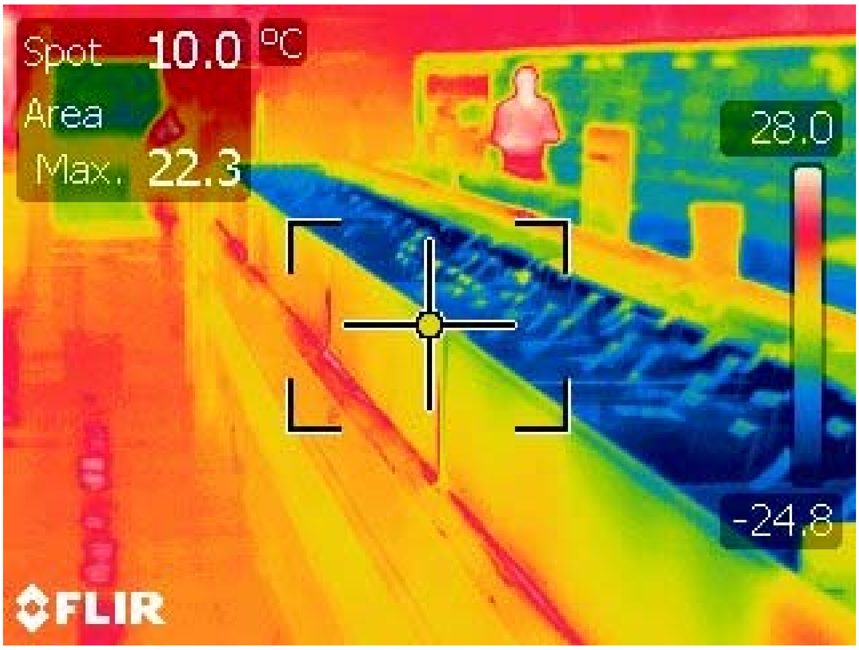

Fig. 11. The aisle is noticeably warmer next to tough freezer because less cold air escapes

Sliding glass lids were retrofitted onto the existing chest freezers and the evaporator fans were replaced with EC units with reduced airflow. This achieved significant energy savings and reduced maintenance requirements.

8. HVAC System

The Heating, Ventilation and Air Conditioning (HVAC) load for this building was 9% of the electricity used in the building. This is comparatively low for a supermarket (can be as high as 30%) and is mainly due to heat recovery from the refrigeration system providing the majority of space heating.

8.1. Pre-Retrofit HVAC

A building of this size and insulation levels would normally display a relatively consistent cooling load in Whanganui’s climate, but from our site observations it is clear that the main retail area is heating much of the year.

The reason is simple. Most of that increased heating load is caused by cool air escaping from the refrigerated displays.

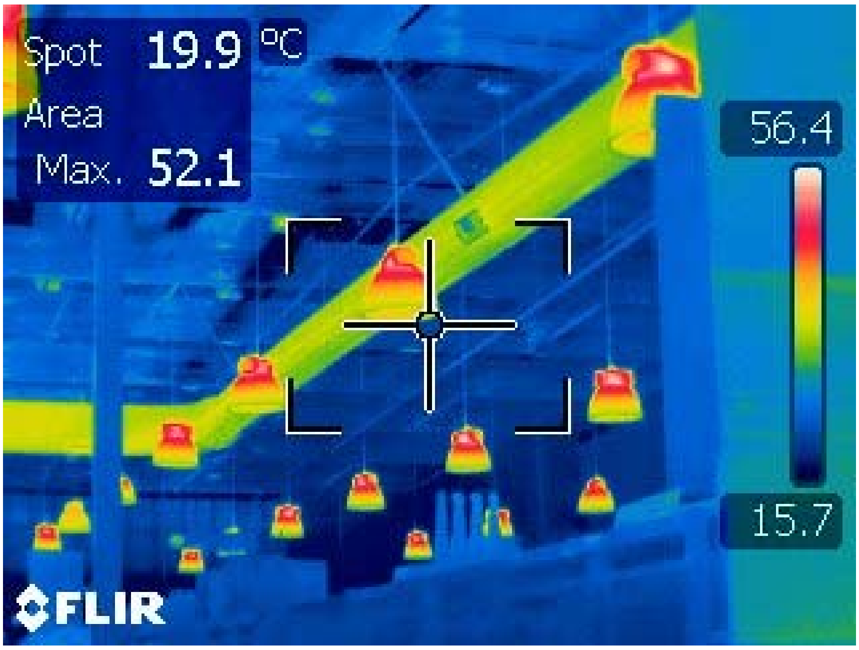

Fig. 12. The AC system supplying warm air to heat the building

The heat taken from the refrigeration system is recycled back into the building through the heat recovery coils in the main AHU, so the cost of heating is greatly reduced.

The main AHU provides cooling with a direct expansion coil, supplied by a bank of three compressors, which operate to cool the supply air into the store. The AHU did not have an economizer or a C02 sensor.

An economizer allows the AHU to supply 100% outside air into the space when required and permits outside air to reduce to zero if combined with a CO2 sensor in the return air duct. Presently the AHU cannot vary the amount of outside air or return air supplied into the space, which can cause increased heating or cooling loads at different times and limits the free cooling available.

8.2. Post-Retrofit HVAC

We installed an economizer on the main AHU to provide energy savings in the summer months and a return air CO2 sensor to optimize the ventilation requirement of the store. The cooling season for the store was quite narrow but installation of skylights and efficient gains in the refrigerated displays means the economizer is used more often.

9. Measurement and Verification

9.1. Sub-metering

We installed nine sub-meters as part of this project:

- Low Temp Refrigeration
- Medium Temp Refrigeration
- HVAC
- Main Foodhall Lighting
- Bakery
- Admin HVAC
- Admin Lighting
- Basement Car Park
- Gas (time of use pulse collected from revenue meter)

These meters have been invaluable for savings verification and analysis. Without these meters we would still be guessing about the actual savings made for each particular ECM implemented.

All of the meter data is available online for the store management and staff to view. This provides motivation for on-site staff and valuable feedback on energy implications of operational changes introduced.

9.2. Savings Verification

All the savings in this project have been verified using Metrix software to IPMVP standards.

10. Project Energy Conservation Measures (ECMs)

Table 2 shows a full list of the ECMs implemented to achieve savings in the store.

Table 2: ECM Table

ECM	*Description*
ECM 1	Skylights & T5 Hi-bays (Dimmed)
ECM 3 & 4	Replace Refrigerated Display Fluorescents with LEDs
ECM 5	Install Economiser & C02 sensors on Main AHU
ECM 7	Daylight Control Entrance Lobby
ECM 8	Daylight Control Car Park Ramp
ECM 9	Fit Night Curtains on Remaining Open Freezer Displays
ECM 10	Replace Open Freezer Displays with Glass Door Freezer Unit
ECM 12	Install LED/T5 Fluorescent Car Park Lighting
ECM 14	Install VSDs on Lead Rack Compressors for Suction Press. Control
ECM 15	Insulate DHW Tank & Ring Main
ECM 16	Replace Freezer Room Fluorescents with LEDs
ECM 17	Replace Chiller Room Fluorescent with LEDs
ECM 18	Reduce Admin Outside Air Fan Volume Flow
ECM 19	Fit Permanent Glass Lids & EC Fans on Trough Freezers
ECM 20	Butchery Prep Area Refrig. to Shutdown Overnight
ECM 21	Produce Prep Area Refrig. to Shutdown Overnight/Permanently
ECM 22	Replace Trough Freezer Honey Cones
ECM 23	Replace Bakery Canopy Lamps with LEDs
ECM 24	Replace Med Temp Refrigerated Display Fans with EC Fans
ECM 25	Install Glass Doors on Liquor Cases
ECM 26	Upgrade Refrigeration Control System
ECM 27	Refrigeration Tune up
ECM 28	Daylight Loading Dock & BOH Store
ECM 29	On-going Three Year Measurement & Verification Plan
ECM 30	Replace Condenser Fans with speed controlled EC Fans
ECM 31	Provide Metering & Sub-metering

11. Conclusion

The major focus of this project was always to achieve substantial energy savings without any negative impact on sales. The surprising result was some of the ECMs we implemented produced positive results in both arenas.

Natural lighting has been the largest of these. Increased light levels in the store resulted in a better shopping environment and serves as a promotional vehicle for the store owner to show sustainability. Everyone can understand that turning lights off saves energy and even sub-conscientiously we all feel better in natural light.

To achieve great natural lighting, the skylight design must be assessed thoroughly but there are a few simple rules that are crucial:

1. 10-15% of the roof area needs to be skylight (12-13% is ideal for our latitude/climate)
2. Try to reduce the width of individual skylights to 600mm or below. More narrow skylights is better to achieve even light levels and avoid hotspots
3. Use skylight materials with UV filtration. Some materials have infrared red filters to reduce heat gain inside the store which is also ideal
4. Install dimmable lighting with automatic control to maintain minimum light levels
5. Ensure the light from the skylight is diffuse. Direct sunlight is to be avoided
6. Always double (or triple glaze) to maximize insulation levels and avoid condensation

Refrigeration is the largest single energy consumer in most supermarkets and has very high potential for savings. The most efficient stores would have doors on every refrigerated cabinet but it would be difficult to convince even the most progressive store owner to do that so it is essential to prioritize.

The impact of doors on savings on savings generated is influenced by a couple of factors in our experience:

1. The colder the cabinet, the bigger the savings (start with low temp as a priority).
2. The worse cabinet (biggest load) on each rack (med or low temp) will achieve the greatest savings
3. Always include commissioning time for the refrigeration engineers to re-tune the system after door installation. The load to a particular cabinet could reduce 30-40% and often the system will require re-adjustment to optimize savings and operation

The sales impact of doors are influenced by the following factors

1. Product type. Doors will have little or no effect on sales of staple products like milk.
2. Promotional cabinets (designed to encourage unplanned purchases) will often suffer more sales impact from door or lid installation.
3. Try to incorporate improved lighting with the door installation. Installation of doors on vertical cabinets provides a perfect position to light product without overheating product (use LED lamps).

The potential for energy reduction in supermarkets is huge. We have achieved 36% energy savings in this store while the total sales increased by 6%, proving that energy efficiency can promote sales. There are still many ECMs we would like to introduce and think 50% savings is possible with further improvement to the customer experience.

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Energy Wheel Performance and Optimization Opportunities for SDVAV AHU's In a Hot & Humid Climate

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Abstract:

The HVAC system accounts for 30 to 50 percent of a typical building's energy consumption; in hot & humid climates it is closer to the upper end of that range. Implementing effective energy saving measures for the building HVAC system can reduce the building energy consumption, reduce peak demand, and improve building comfort. The energy wheel is widely used in new system designs to recover/reject both sensible and latent heat energy from/to the exhaust airflow of air handling units. In this study, field measurements were conducted to evaluate the performance of one energy wheel installed in a SDVAV AHU serving an education building on a large university campus located in a hot and humid area. This paper also presents recommended optimization and performance improvement opportunities associated with this unit based on the performance evaluation.

Keywords:

Air handling unit, Energy efficiency, Energy wheel, Performance Improvement

1. Introduction

The air-to-air rotary energy wheel, as a widely-used energy recovery unit, is used in building HVAC system to recover/reject both sensible and latent heat energy from/to the exhaust airflow of air handling units. The air-permeable medium filled in the revolving cylinder of the energy wheel provides large heat and mass transfer area to make the rotary energy wheel has the potential to obtain high sensible and latent heat recovery effectiveness. The advantages for applying the energy wheel as an energy recovery unit include: (1) simultaneous heat and mass transfer, (2) low pressure drop, (3) compact size, and (4) available to all ventilation system platforms; the limitations of the energy wheel application include: (1) further cooling/heating required for supply air, (2) possible cross-contamination, and (3) increased maintenance requirement under cold climate (ASHRAE, 2005).

Field testing helps to increase the confidence in energy wheel performance and promote the application of such energy-recovery devices (Zhai, et al., 2006). ASHRAE Standard 84-1991 provides guidance for laboratory testing for air-to-air enthalpy exchangers. As the enthalpy exchanger performance in the field may differ from lab application, using ASHRAE Standard 84-1991 for field performance testing is not as applicable as it is to the laboratory testing. In winter 2006, a field testing and a lab testing were performed on the enthalpy recovery wheel installed in the ventilation system of Carnegie Mellon University's Intelligent Workplace (Zhai, et al., 2006). The testing used manufactured installed instruments as well as temperature and humidity data loggers. The results show that the field testing performance matched the lab testing. The manufacture-installed sensors show 27 % discrepancy between the heat loss and heat gain. This discrepancy was reduced after implementing the purge flow to the heat balance calculation. Meanwhile, complicated heat and mass transfer equations or numerical models were developed to predict the enthalpy wheel performance. For example, Klein (Klein, et al., 1990) developed a ε-NTU model for the silica gel enthalpy wheel. Simonson and Besant (Simonson, et al., 1997) used the finite volume method (FVM) to develop a numerical model for the enthalpy wheel. Beccali (Beccali, et al., 2003) and Freund (Freund, et al., 2003) proposed simpler models for predicting the correlation for sensible, latent and total effectiveness of enthalpy wheels, but these models were still complicated and had some deficiencies; for instance in Freund model, manufacture's effectiveness data were used for determining the correction factors. Knowing that manufactures usually provide performance data for standard operating rates, Freund's model would be complicated for non-standard performance conditions. Jeong and Mumma (Jeong, et al., 2005) developed simpler method to provide reliable enthalpy wheel effectiveness correlations readily applicable to design and analysis of enthalpy wheel applications. In their research the 2^k factorial experiment design method is applied to analyze the enthalpy wheel effectiveness correlations for six variables: incoming outdoor air (OA) temperature and relative humidity, exhaust air (EA) temperature and relative humidity, face velocity and EA to OA flow ratio. In total $2^6(64)$ experiments on silica gel and molecular sieve enthalpy wheels were performed for the full factorial experiment. A. S. Al-Ghamdi (Al-Ghamdi, 2006) developed numerical models to study the effect of some parameters such as rotational speed, number of transfer unit, heat capacity ratio, porosity and volume flow rate on wheel effectiveness during summer and winter operations.

The performance of a rotary energy wheel is evaluated by the wheel effectiveness (e.g., sensible/latent/total effectiveness) and the wheel medium pressure drop. Under different weather conditions (e.g, dry and cold condition, humid and hot condition), the energy wheel is used for humidification or dehumidification besides of recovering sensible heat. This study focuses on an energy wheel installed in a single duct VAV air handling unit and operated under a hot and humid weather. The real-time trending data were used to estimate the wheel effectiveness. The purpose of this study is to use field data to evaluate an energy wheel performance in a hot and humid climate and identify potential performance improvement opportunities based on current operation sequence for future CC® services.

2. Case Study and Method

2.1. Study Site and Device Introduction

The study building locates on a large campus and contains offices, lecture halls, laboratories, and conference rooms. Local climate is subtropical and temperate. It is hot and humid in summer season. The air handling unit, installed with the studied energy wheel, services the lab areas of the building. Figure 1 shows the schematic diagram of the studied AHU. The part of return air re-enters service area through a by-pass damper installed between supply duct and exhaust duct. The trending data shows the supply air flow is about 3 times of the exhaust air flow. According to current operation sequence, the energy wheel operates when outside air (OA) dry-bulb temperature is less than 50 ^{o}F or greater than 60 ^{o}F. The energy wheel has VFD installed; the VFD speed is controlled based on OA dry-bulb temperature (Table 1). The design information of the energy wheel is listed in Table 2.

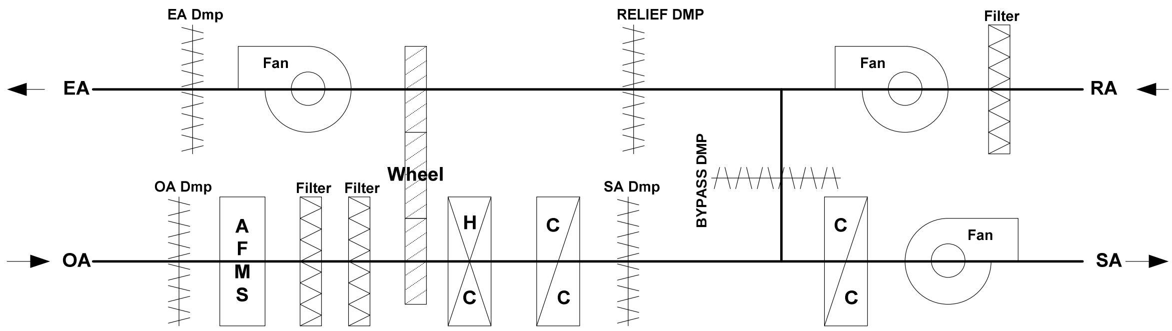

Fig. 1. Schematic diagram of AHU with studied energy wheel installed

Table 1: Energy wheel speed control sequence

OAT, ^{o}F	35	50	70	85
Wheel VFD SPD, %	100	20	20	100

Table 2: Mechanical schedule of the energy wheel

Supply Air				Exhaust Air			Total Eff.	Motor HP	Vol/PH/HZ	RPM
CFM	EAT DB/WB	LAT DB/WB	Wheel "H_2O	CFM	EAT DB/WB	Wheel "H_2O				
8,000	97/80	84.1/70.8	0.9	5,125	76.5/64	0.9	95 %	1.0	460/3/60	1725

2.2. Field Measurement Instruments and Method

The field measurements were taken for (1) entering air temperature/relative humidity and leaving air temperature/relative humidity of the energy wheel in supply side and exhaust side, (2) pressure drop of the energy wheel at different VFD speeds, and (3) air flow rate in supply side and exhaust side. Instruments used for taking these measurements include Fluke thermometer and VELOCICALC multi-function ventilation meter (Figure 2). The measurements were taken in the mixing chamber before and after the energy wheel. During measurements, the supply fan and the exhaust fan VFD drives were manually locked to maintain constant supply and exhaust air flow. Meanwhile, the energy wheel VFD was controlled to be different speed (e.g., 20 %, 60 %, 80 %, and 100 %) to take the measurements. The measurements were taken at the same time range to avoid fluctuation of supply side entering air temperature and exhaust side entering air temperature.

Fig. 2. Fluke thermometer (left) and VELOCICAL multi-function ventilation meter (right)

Besides of field measurements, HoBo data loggers were installed in the mixing chambers before and after the energy wheel to trend real-time (every 5 minutes) air dry-bulb temperature and relative humidity of supply and exhaust air stream for one week. The energy wheel speed, supply air flow and exhaust air flow were trended using the sensors installed in AHU through Siemens Apogee control system. The field measurements were taken to verify these sensors to ensure the accuracy of the trending data.

2.3. Energy Wheel Effectiveness Calculation

ASHRAE Standard 84 defines energy wheel effectiveness as:
$\varepsilon = \frac{Actural\ transfer\ of\ moisture\ or\ energy}{Maximum\ possible\ transfer\ between\ airstreams}$. (ASHRAE Handbook, 2008) According to energy transfer process, effectiveness is given as sensible effectiveness (the sensible heat transfer process), latent effectiveness (the moisture transfer process), and total effectiveness (total energy transfer including sensible heat transfer and moisture transfer). In this study, three effectiveness values were calculated based on the trending data. Figure 3 shows a schematic diagram of counter-flow airstreams through energy wheel.

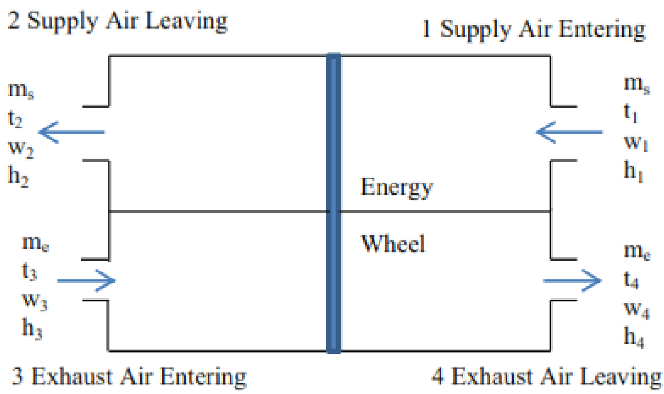

Fig. 3. Schematic diagram of counter-flow airstreams through energy wheel

The sensible effectiveness is calculated using Equation (1). This equation is applicable under the conditions: (1) no heat or moisture transfer between the wheel and surrounding, (2) no cross-leakage, (3) no energy gains from motors, fans, or front control devices.

$$\varepsilon_s = \frac{q_s}{q_{s,max}} = \frac{m_s c_{ps}(t_2 - t_1)}{C_{min}(t_3 - t_2)} = \frac{m_e c_{pe}(t_3 - t_4)}{C_{min}(t_3 - t_1)} \quad (1)$$

Where

t_1, t_2, t_3, t_4 = dry-bulb temperature at locations 1, 2, 3, and 4 in Figure 3, °F
m_s, m_e = supply and exhaust dry air mass flow rate, lb/min
C_{min} = smaller of $c_{ps}m_s$ and $c_{pe}m_e$
c_{ps}, c_{pe} = supply/exhaust moist air specific heat at constant pressure, But/lb.°F

The latent effectiveness is calculated using Equation (2).

$$\varepsilon_L = \frac{m_s(w_1 - w_2)}{m_{min}(w_1 - w_3)} = \frac{m_e(w_4 - w_3)}{m_{min}(w_1 - w_3)} \quad (2)$$

Where

w_1, w_2, w_3, w_4 = humidity ratio at locations 1, 2, 3, and 4 in Figure 3
m_{min} = smaller of m_s and m_e

The total effectiveness is calculated using Equation (3).

$$\varepsilon_t = \frac{m_s(h_1 - h_2)}{m_{min}(h_1 - h_3)} = \frac{m_e(h_4 - h_3)}{m_{min}(h_1 - h_3)} \quad (3)$$

Where

h_1, h_2, h_3, h_4 = enthalpy at locations 1, 2, 3, and 4 in Figure 3, Btu/lb

3. Results

24 hr data logger trending data in a hot and humid day was used to calculate sensible effectiveness, latent effectiveness, and total effectiveness of the energy wheel. The calculated total effectiveness of the wheel under the hot and humid weather was about 80 %, which is lower than the design value (95 %). Following plots (Figure 4 to Figure 6) show the calculated sensible/latent/total effectiveness of the energy wheel and relationship between the wheel effectiveness and OA dry-bulb temperature/humidity/wheel speed.

3.1. Energy Wheel Effectiveness vs. OA Dry-Bulb Temperature

Figure 14 shows lower (comparing to the effectiveness values when OA dry-bulb temperature is much higher than the exhaust entering temperature: space temperature- 74 ^{o}F) wheel effectiveness (sensible/latent/total) when OA dry-bulb temperature is closed to the exhaust entering temperature (space temperature). It seems, from trending data, the significant influence is on the wheel sensible effectiveness. However, the potential influence of trending data accuracy on the sensible effectiveness calculation should be considered for this OA temperature range. On the other hand, this observation shows the performance of an energy wheel at this OA temperature range may be declined.

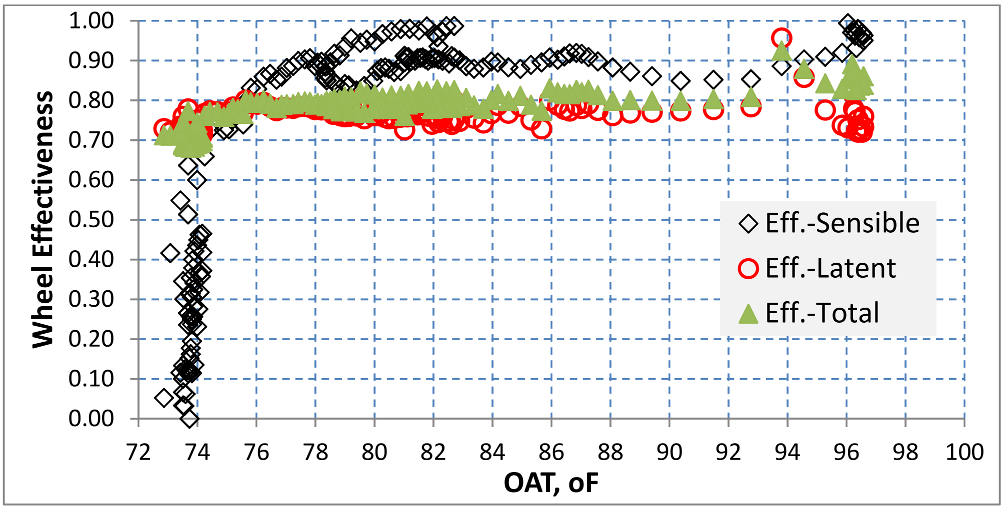

Fig. 4. Wheel effectiveness vs. OA dry-bulb temperature

3.2. Energy Wheel Effectiveness vs. OA Humidity (Dew Point Temperature)

Figure 5 shows the wheel works more efficient (average 80 % total/latent effectiveness, average 90 % sensible effectiveness) at high OA humidity condition comparing to lower humidity condition (average 70 % total/latent effectiveness, average 50 % sensible effectiveness).

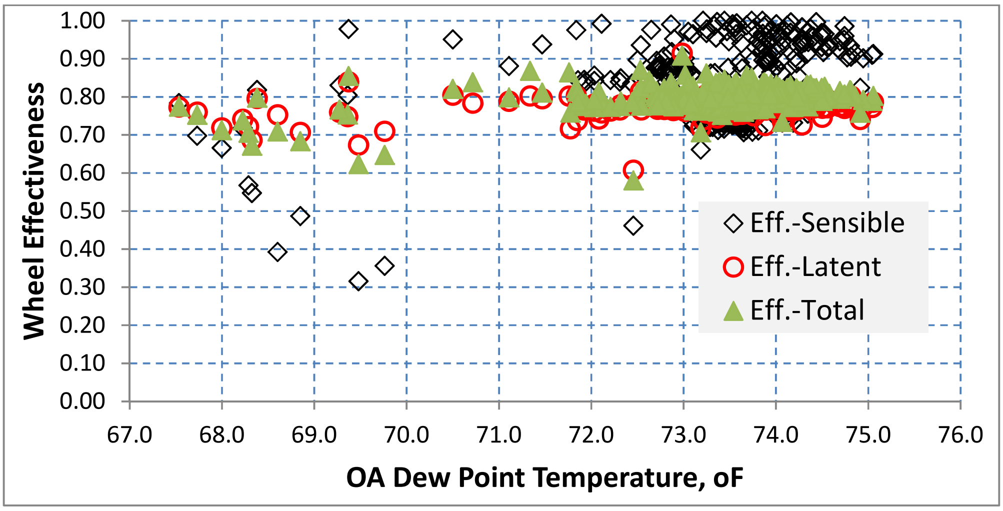

Fig. 5. Wheel effectiveness vs. OA dew point temperature

3.3. Wheel Effectiveness vs. Wheel VFD Speed

It shows in Figure 6 that the wheel effectiveness has small improvement when the wheel VFD speed is above 90 %. However, the wheel VFD speed effect on the wheel effectiveness is not significant.

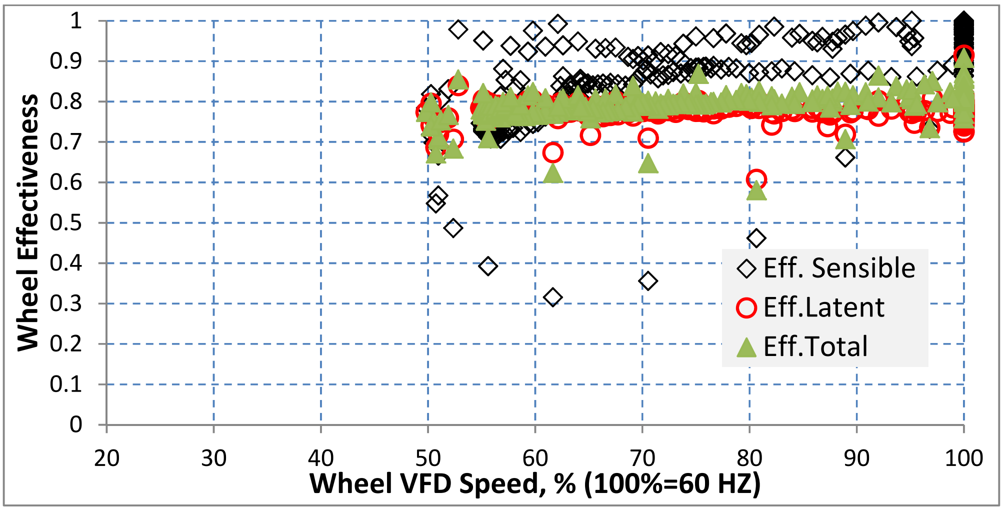

Fig. 6. Wheel effectiveness vs. wheel VFD speed

3.4. Field Estimation of Power Recovery of the AHU Installed with Studied Energy Wheel at Different Wheel Speeds

Besides of data logger trending data, field measurements were conducted to estimate power recovery from the energy wheel operation and power consumption from the energy wheel and supply fan power used to overcome pressure drop through the wheel. During measurements, the

VFDs of the supply fan and the exhaust fan were overridden to maintain fixed supply air flow (7,650 cfm) and exhaust air flow (4,207 cfm). And, the measurements were taken at the same time range to avoid fluctuation of supply side entering air temperature and exhaust side entering air temperature. The wheel VFD speed was controlled to be at 20 %, 60 %, 80 %, and 100 % respectively. Table 3 shows the calculated results, which show higher power recovery at high wheel speed. Meanwhile, the pressure drop is similar for each wheel speed.

Table 3: AHU power recovery at different wheel speeds

WHL SPD, %	**Wheel Pressure Drop, inch WC**	**WHL electrical power consumption, kw**	**Wheel power recovery, kw**	**Supply fan power consumption, kw**	**Net power recovery, kw**
20	0.65	(0.0039)	48.58	(16.29)	32.28
60	0.62	(0.168)	45.42	(15.94)	29.31
80	0.57	(0.434)	63.03	(13.03)	49.57
100	0.64	(0.746)	67.8	(16.39)	50.67

4. Summary and Recommendations

4.1. Summary

This study uses real-time trending data collected in a hot and humid day to estimate the sensible/latent/total effectiveness of an energy wheel installed in a single duct VAV air handling unit with the configuration in Figure 1. Meanwhile, the field measurements were conducted to estimate power recovery of the AHU for different wheel speeds. The operation performance of the studied energy wheel in a hot and humid climate is summarized as follows:

- The total effectiveness obtained from trending data is lower than the design value (80 % vs. 95 %).
- The performance of the wheel declines when OA dry-bulb temperature is closed to space temperature (exhaust air entering temperature).
- The wheel speed has not significant influence on the studied wheel effectiveness.
- The application of the energy wheel under hot and humid weather recovers energy.

This study focuses on an air-to-air rotary energy wheel installed in a single duct VAV AHU to do a preliminary evaluation of the performance of the wheel operating in a hot and humid climate. The real-time trending data and field measured data were taken when the unit operated normally. The results of this study show the performance of the studied energy wheel in its practical use. The extended studies will be needed to verify whether the performance observations from this study are applicable to other energy wheels installed in the AHUs with different configurations.

4.2. Recommendations

Based on the review of current wheel operation sequence and preliminary performance evaluation, the recommended energy wheel performance improvement opportunities are as follows:

- The by-pass damper in supply side of the AHU with the energy wheel installed should be available to implement economizer mode when the wheel is off.
- The OA dry-bulb temperature based wheel speed control should be optimized according to weather condition.

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Development of an Automated Fault Detection and Diagnosis tool for AHU's

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Abstract

Heating Ventilation and Air Conditioning (HVAC) system energy consumption on average accounts for 40% of an industrial sites total energy consumption. Studies have indicated that 20 – 30% energy savings are achievable by re-commissioning HVAC systems to rectify faulty operation with savings of over 20% of total energy cost possible by continuously commissioning.

Automated Fault Detection and Diagnosis (AFDD) is a process concerned with automating the detection of faults and their causes in physical systems. AFDD can be used to identify faults in HVAC systems with a view to reducing their energy consumption.

An AFDD tool has been designed and developed to allow the performance analysis of AHU's by utilising knowledge-based principles. Based on an initial alpha testing phase on 12 AHU's across four large industrial pilot sites, in excess of €120,000 of energy savings have been detected by the AFDD tool and verified by site survey.

Keywords

Continuous Commissioning, Fault Detection, HVAC

1. Introduction

The contribution of buildings towards total worldwide energy consumption in developed countries is between 20% and 40%. This is expected to rise by an average rate of 1.5% per annum over the next 20 years [1]. Heating Ventilation and Air Conditioning (HVAC) energy consumption accounts on average for 40% of an industrial sites total energy consumption[2] due primarily to the stringent cleanliness requirements that many of the industrial processes require to be in compliance with international standards[3].

Approximately 50% of a commercial building's energy consumption is associated with HVAC energy consumption [4]. Overall, it is estimated that HVAC energy consumption accounts for 10 – 20% of total energy consumption in developed countries [1].

Buildings rarely perform as well in practice as anticipated during design due to improper equipment selection or installation, lack of commissioning, or improper maintenance [5] to cite but a few reasons. Studies have indicated that 20 – 30% energy savings are achievable by recommissioning HVAC systems to rectify faulty operation [6]. Studies have also demonstrated, using a sample set of over 80 buildings, that continuous commissioning of building systems for peak efficiency can yield savings of an average of over 20% of total energy cost [5]. By coupling the re-commissioning and ongoing commissioning of a HVAC system into one demonstration study, savings of 44% of electricity consumption and 78% of gas consumption over a ten year period have been proven by the International Energy Agency (IEA) Annex 47, DABO Case Study[7], [8].

Building Energy Management Systems (BEMS) are typically the repository of HVAC system data and are now commonly installed in commercial and industrial buildings [9]. The availability of BEMSs offers the potential for innovative commissioning services with lower set-up costs than cases where a BEMS is not present. Automated Fault Detection and Diagnosis (AFDD) is a process which could utilise this BMS generated data to automatically detect faults and their causes in physical systems [10].

1.1 HVAC system management

HVAC systems are typically supervised and maintained by either an onsite facilities team or an offsite third party contractor. Based on the companies involved in this project, the number of Air Handling Units (AHU's) in a typical HVAC system often outnumbers those supervising and maintaining the system by 20 to 1. This means that routine mechanical maintenance is typically carried out only when necessary due to an end user complaint, a machine breakdown or a critical breached alarm limit. The complexity of modern HVAC system control systems also commonly results in onsite personnel not having the required knowledge to root cause issues without costly external consultancy.

Both top down (system level) and bottom up (component level) approaches are common methods of managing HVAC system operation in terms of optimising their energy consumption and achieving other operational targets. The top down approach is growing in its application though it is not yet commonplace. Many industrial and large/multi commercial sites now employ Monitoring & Targeting (M&T) approaches, energy performance indicators, and performance dashboards to manage site energy consumption. Typically these systems focus on the most significant energy end-uses, of which HVAC is typically one. Structured energy management systems such as those in compliance with En16001 [11] or ISO50001 [12] promote this philosophy of energy management and are growing in their adoption.

The bottom up approach is far more common in practice. This method has developed from breakdown maintenance of key HVAC system components, such as fans and filters; to time based maintenance; to today's common process of monitoring equipment based on its condition and then carrying out maintenance tasks as required.

1.2 BEMS assisted HVAC system monitoring

BEMS systems are commonly used to supervise the performance of HVAC systems, raising alarms when upper or lower limits of operation are breached. However, they do not diagnose the root cause of these alarms. The sheer number of these alarms coupled sometimes with a lack of understanding as to their root cause, can result in maintenance personnel ignoring, or accepting them without due diligence. Furthermore, when no alarm levels are breached, they do not detect underlying faults during what appears to be normal operation of these systems. A typical example is the refrigeration energy wasted by a passing cooling coil control valve, as illustrated in Figure 1 by the drop in temperature across the cooling coil in the Air Handling Unit (AHU) when the control valve is showing closed. This particular example typically goes unnoticed for long periods of time, as it is often possible for the AHU to maintain control of all set-points due either to the availability of hot return or outside air or due to the availability of a heating coil up or downstream to compensate for the temperature drop across the cooling coil.

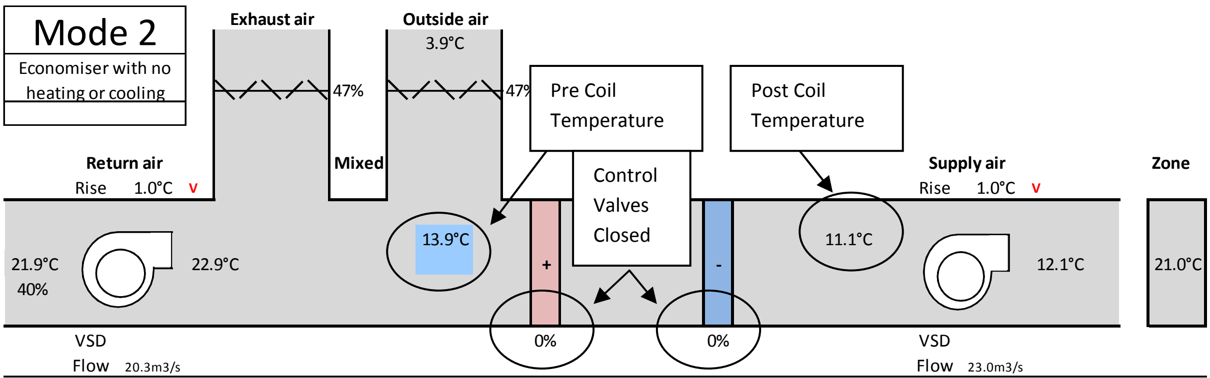

Figure 1: Example of a typically undetected fault in a cooling coil control valve

2. How can an AFDD tool help?

As HVAC systems grow more complex, so too will the maintenance and commissioning processes required to ensure their efficient operation in terms of ensuring adequate air changes and differential pressure balances.

If current trends continue this movement towards more complex systems will result in a more expensive and lengthy maintenance and commissioning processes. As current practices are mostly manual and hence, costly, this will further decrease the likelihood of their ongoing success. For these reasons, the manual nature of maintenance and commissioning is set to change, moving towards an automated method. AFDD is a key means of achieving automated commissioning with many AFDD projects now in the implementation phase from their initial research and development [4]. IEA Annex 47 [7] reviewed the operation of 18 such tools, concluding that automation is still uncommon during the maintenance & commissioning processes, and that future tools should be developed that are easily embedded in existing operational practices. An AFDD tool could hence reduce the cost of both maintenance and commissioning activities, while improving the overall energy efficiency of HVAC systems in the process.

3. AFDD Tool Development

The primary objectives for the AFDD tool being developed as part of this project are:

- Flexibility to work with any BMS
- Flexibility to work with any combination of sensors and components found in typical AHUs;
- To use already available measurement without the need to install additional sensors;
- Capable of evaluating the ongoing performance of AHUs;
- A rapid setup time of the automated FDD tool per AHU;
- A very low number of false positives/negatives in order to build confidence in the tool;
- Quantification and prioritisation of the diagnosed faults

In order for the FDD tool to operate automatically, automated collection of the measured data from AHUs is essential. Figure 2 illustrates the overarching system architecture utilised to develop the AFDD tool.

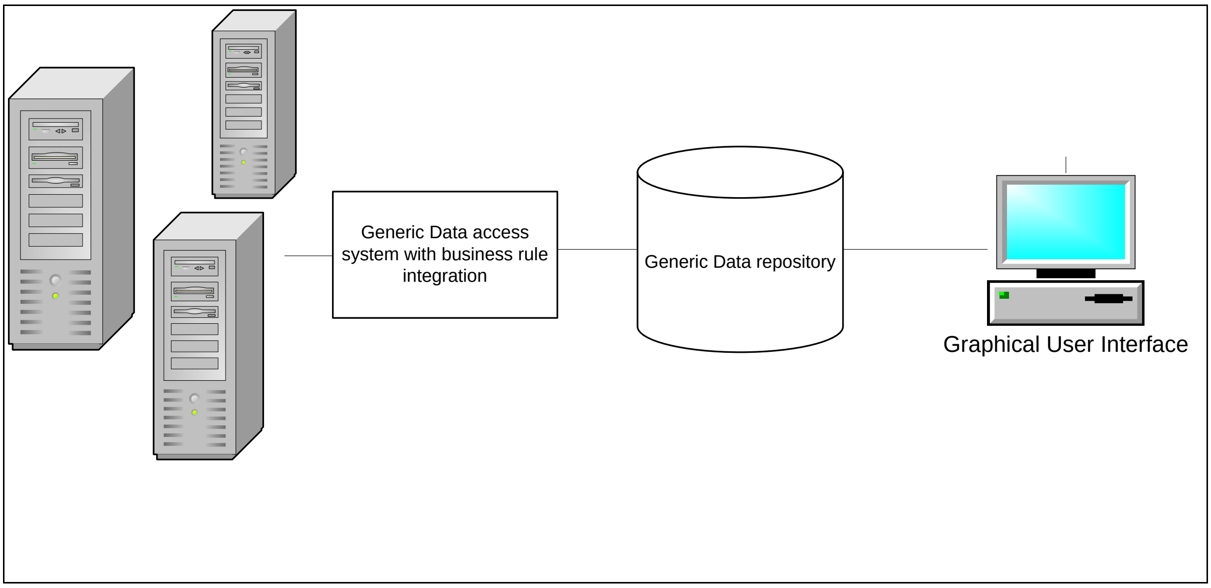

Figure 2: AFDD tool system architecture

3.1 Data Access

There are a number of issues that cause difficulty in obtaining BMS data and transferring it to a database for analysis. Firstly, there are different BMSs in operation across the pilot sites (see Table 1). Each BMS software has its own proprietary method of archiving data. The archiving methods cover a wide range from very primitive (e.g. one comma separated value file for each sensor/or component in which each line in the file corresponds to a daily dump of all of the values stored on the controller) to advanced (e.g. a normalised relational database). Secondly, the issue of getting robust data is exacerbated by the age of the BMS software on some sites. There are often missing values, irregular timestamps and spurious outliers in the data that need to be corrected or removed from the dataset. Thirdly, measured data from the pilot AHUs was not archived at all on many of the sites and needed to be set up as part of initial configuration activity. A generic data access tool was hence developed which could upload BMS data from the client server irrespective of the type of BMS software being utilised.

Table 1: Characteristics of BMS and data acquisition methods on each site.

Site	BMS manufacturer	Status of data acquisition	Typical frequency of logged data	Logging hysteresis	Method of data acquisition
1	Trend	Daily	15 minutes	No	Web service application
2	Satchwell	None	15 minutes	Unknown	None
3	Cylon	Daily	15 minutes	No	Web service application
4	Cylon	Daily	15 minutes	No	Web service application
5	Custom	Weekly	5 minutes	No	Custom tool
6	Honeywell	Manual	15 minutes	Yes	Manual

3.2 Generic Data

Once uploaded via the data extraction tool, the data had to be parsed to ensure it was generic across all sites. As there was no common naming convention used across all of the BMSs, each sensor/component id tag on the BMS has to be mapped to a particular sensor/component in the database format. The naming convention for each recorded value is then standardised within both the database and the AFDD tool so that different AHUs can easily be compared at a glance. Next, all of the values are converted to a single format for clarity and ease of use across all sites and AHUs. Then, all data is averaged into hourly bins~~,~~ and fault diagnosis is performed on these hourly values. This is an attempt to smooth out variability in the data due to the dynamic nature of the processes in the AHU. Finally, the processed measured data for each site is then stored in a remotely hosted relational database management system (RDBMS) using MySQL. Static information about each AHU is also required in addition to the measured BMS data~~,~~ acquired during an initial site survey.

3.3 Fault Identification

Correct identification of the mode of operation of an AHU is critical to identifying how each component should operate, and therefore, critical to performing FDD. Approaches to date have focused on determining the operating mode of the AHU by identifying the actual operating mode from the outside air damper position, cooling and heating coil valve positions

[13–15]. The tool described in this paper incorporates this approach but with some additions to increase effectiveness.

The business layer of the AFDD tool was developed from the APAR rule set [13] with the following modifications:

- Expansion to account for other possible configurations of components and sensors:
  - Frost coils;
  - Reheat coils;
  - Off coil temperature sensors;
  - Before and after fan temperature sensor positions.
- Expansion to account for faults that are apparent when the AHU is off:
  - Open valve positions;
  - Unusually high or low off coil air temperatures.
- Addition of virtual temperature data:
  - The temperature before or after a fan using an estimate for the rise in temperature across the fan
  - The mixing box temperature
  - The average outside air temperature.
- Rearrangement to account for the ideal mode of operation
- Rearrangement to account for the an improved error threshold approach

A client side side application performs the mode checks, calculates the virtual values, applies the business layer rules, and stores the results in the database. The business layer has been designed so that it can be conveniently broken down into categories, several examples of which are described in Figure 3.

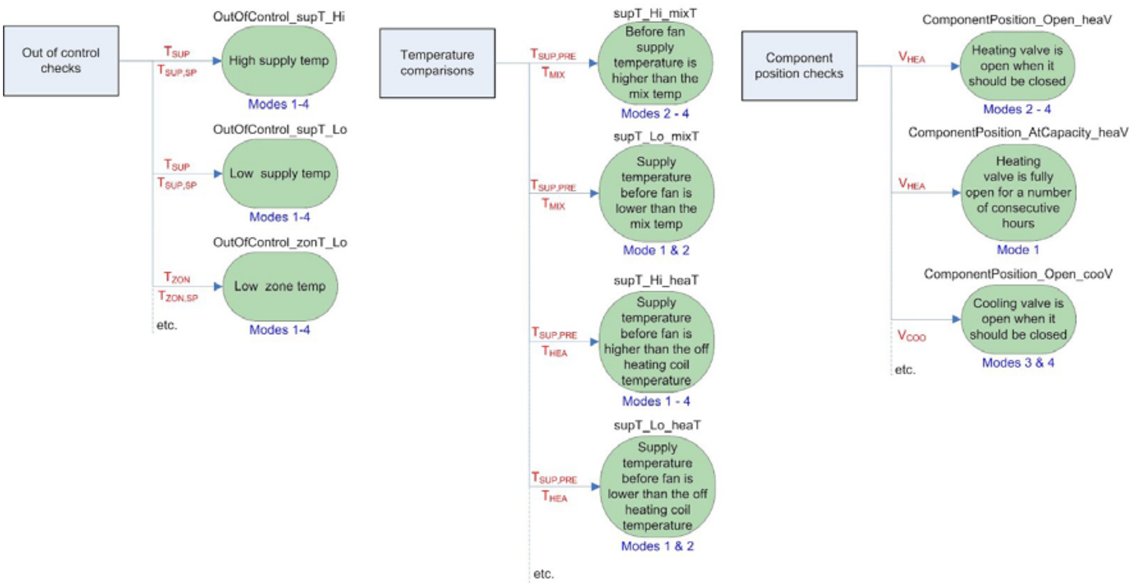

Figure 3: Examples of the business rules

3.4 Improving Fault Identification Accuracy

A key issue identified in the early phase of this project was the use of a single, heuristically defined error threshold value that was applied to all of the rules. The purpose of this error threshold is to reduce false positives: where a fault is identified by the tool but none is present in the AHU. This error threshold is intended to account for all of the inaccuracies in measurements due to sensor error, sensor location, whether the measurement is taken using an averaging or point sensor, and the dynamic nature of AHU operation.

A major issue with previous approaches is that the actual error associated with each rule is dependent on the number and type of measurements used in a particular rule. For example, a rule using just one measurement from an averaging temperature sensor should have a lower error threshold than a rule using 3 measurements from a variety of sensors.

The approach used in this tool allows the user to define an individual error threshold associated with each sensor. The error thresholds for each sensor measurement used in a fault check are then combined to yield a rule-specific error threshold.

3.5 Graphical User Interface

A Graphical User Interface (GUI) has been developed for the AFDD tool. The GUI has been built in Microsoft Excel using Visual Basic for Applications (VBA). This tool is very much a development tool which will be transitioned to a more scalable solution later in the project. The GUI allows the user to:

- Set up new AHUs in the AFDD tool;
- Modify set up parameters
- Visualise AFDD results

The GUI automatically generates a schematic of the AHU based on the components and sensors that are present within the unit. Users can select any particular instance of time to be presented on this schematic. This feature allows the user to quickly view a representation of the AHU under any past operating conditions allowing fault instances to be analysed in more detail.

All identified faults are listed by frequency of occurrence in the analysed period. Once a particular fault is selected, the GUI displays:

- The measured and virtual data on the schematic for the most recent hour in which the fault occurs
- A textual description of the currently displayed fault;
- A graphical trend of the past 48 hours of values relevant to that fault;
- Options to move to other instances of that particular type of fault in the analysed period;
- A list of possible diagnoses for the currently displayed fault;
- A list of other faults which occur during the same hour;
- The current operating mode of the AHU

This allows for rapid viewing of individual faults, but still requires partial user input to root cause the fault.

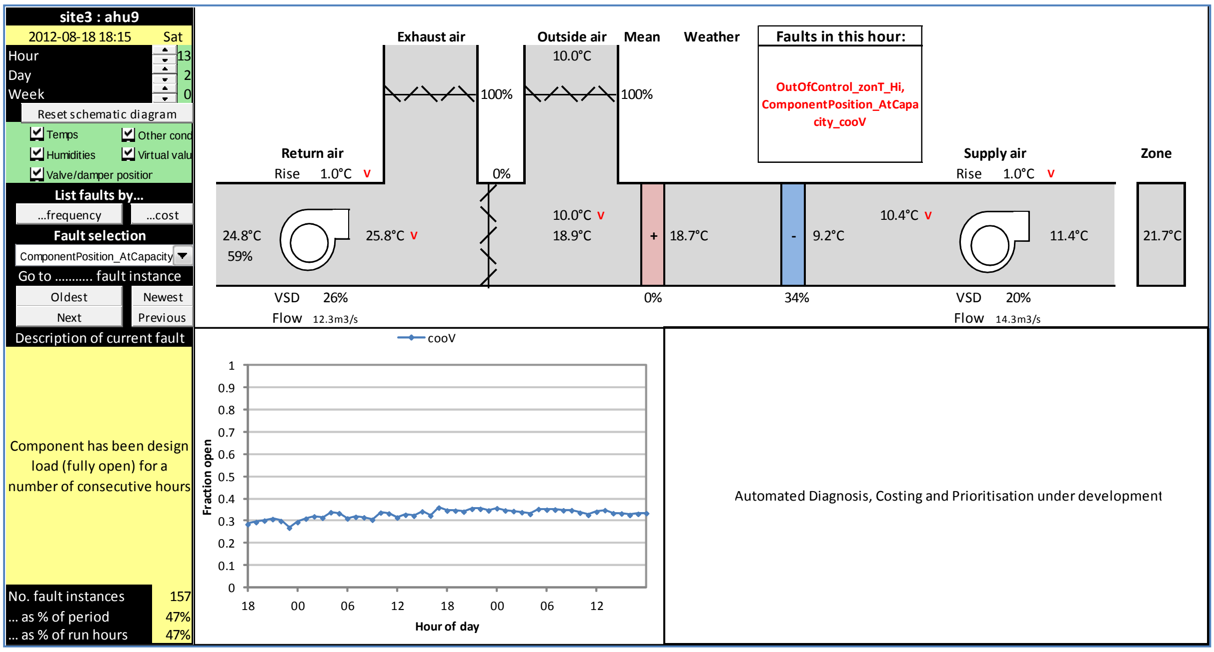

Figure 4: Screenshot of the GUI indicating an out of control zone air temperature

4. Pilot Study

4.1 I2E2

The Innovation for Ireland's Energy Efficiency (I2E2) Energy Technology Centre is an Irish government sponsored Centre. I2E2 was established to facilitate research that will have a direct impact on energy efficiency in industry internationally. The I2E2 research focus is on energy efficiency improvements in manufacturing processes and supporting systems. The current research agenda focuses on a number of areas of common interest to group members, one of which is HVAC systems. The original scoping of the HVAC project started in January 2009 and the project currently involves 2 research providers and 6 industry partners. The main objective of this research is to provide an automated FDD tool that has been extensively tested on a range of different AHUs across a number of disparate industrial sites

4.2 Pilot Study Outline

Several hundred AHUs were available for selection due to the scale of the industrial sites involved in this collaboration project. A number of characteristics were taken into consideration in order to select a number of representative units for the purpose of developing and validating the tool. As such, AHUs were selected with the following characteristics:

- Different component and sensor layouts in order to ensure that the AFDD tool can be applied effectively and comprehensively;

- Varying levels of instrumentation in order to alleviate concerns regarding the level of instrumentation needed to perform FDD effectively;
- The potential for duplication to ensure scalability to maximise savings.

In addition to the selection criteria, return air units with mixing boxes were selected as these are more complex than full fresh air units and hence have the potential for more faults. Furthermore, mixing units incorporate all the components and sensors found in full fresh air systems ensuring that, once proven for return air units, the AFDD tool could be relatively easily expanded to apply to full fresh air units. Figure 5 shows a picture of one of the pilot AHUs.

Figure 5: Picture of one of the pilot air handling units.

Table 2, in which the industry partners are anonymous, describes the major characteristics of each pilot AHU, which were selected to offer varying component and sensory distributions.

Table 2: Major characteristics of the pilot AHUs

Site	No. of pilot AHUs	Type	Design maximum airflow [m3/s]	Supply fan motor power [kW]	Return fan motor power [kW]	Multi zone unit	Type of zone(s) supplied	Operating hours per annum
1	2	CAV	14	30	15	Y	Office & canteen	8760
2	1	CAV	15	Not available	Not available	N	ISO class 7 cleanroom area	8760
3	4	CAV	Not available	45	22	N	Production area	8760
4	10	VAV	13	10	N/A	N	Manufacturing Floor	6240 and 3640
5	4	VAV	22	75	37	Y	Office	8760
6	1	VAV	14	45	25	Y	Office	3120

4.3 Results from pilot phase testing of the AFDD tool

4.3.1 General Observations

The most unexpected observation during the pilot study was the number of potential opportunities for improvement present in each of the pilot AHU's. The AFDD tool identified numerous physical and control system faults with all the units under analysis.

Manual interaction with the AHU's was identified as a major cause of energy inefficiency in the HVAC units under observation. Supply and zone set points were found to be manually adjusted to overcome what were actually ineffective control issues or physical faults in the system

There were significant difficulties encountered in obtaining data from the on-site BMSs due to a wide variety of issues. Most of these issues could be resolved by developing and using a standard that would provide a consistent naming convention for sensors and components and a normalised relational database schema for archiving long term BMS data. Unfortunately, to the best of the authors' knowledge, no such standard currently exists.

Aside from the issues in obtaining measured data, it was quite difficult to obtain design details of some AHUs. This was due to the age of many of the AHUs (resulting in a lack of documentation), frequent retrofits that have occurred on most sites (as the requirements for manufacturing environments change quite regularly), and difficulty in physically accessing the units in order to obtain measurements using temporary sensors and handheld devices.

4.3.2 Energy Savings identified by the AFDD tool

The AHUs on several of the sites have been analysed in detail using the AFDD tool and a number of faults have been detected. Table 4 provides an overview of the faults identified to date across the pilot AHU's and their associated costs which totalled over €121,000. These faults have been verified by physical inspection using airside measurements. The costs associated with the faults were estimated assuming conservative annualised unit costs of associated energy.

Table 3: Savings identified to date.

Site	No. of AHUs investigated	Faults identified by the FDD tool	Annual savings opportunities (approx)	Verification method
1	2	Passing heating coils	€48k	Physical (airside) survey by the authors

3	4	Damaged dampers, low supply temperature, passing cooling coil	€23k	Physical (airside) survey by the authors
4	4	Damaged dampers	€3k	Physical (airside) survey by the authors
5	4	Poor design, passing frost coils & incorrect set-points	€44k	From extensive BMS data and confirmed independently
6	1	Passing heating coil, poor frost protection control setup, leaking dampers	€3k	Independent physical survey

5. Future work

Currently, the business layer of the AFDD tool is procedural in design. While this was appropriate in order to rapidly test the initial FDD method for a limited number of AHUs, this approach is not effective on varying types of AHU's. Therefore, the next step is to redevelop the business layer using an object-oriented approach to allow its expanded and scalable use across all types of AHU's. In conjunction with this work, further capabilities will be added to consider different types of faults, such as fan, motor, filter and variable frequency drive (VFD) faults using the pressure, power, and flow sensor data that is available in many of the AHUs.

Other future work will focus on further validation of the savings using an established international standard for measurement and verification such as ASHRAE Guide 14[16] of the International Measurement and Verification protocol (IPMVP) [17].

Fully automated fault diagnosis is the key next step in the project. As described earlier, users must currently manually diagnose the root-cause of a particular fault given a number of suggested possibilities. A method to fully automate this process is currently under testing in conjunction with the development of a method of prioritisation to aid end users in selecting which faults to repair first.

6. Acknowledgement

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Model Based Building Chilled Water Loop Delta-T Fault Diagnosis

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Abstract

Improving chilled water delta-T, which is the temperature difference of chilled water supply and return temperature, in campus buildings that are connected to a central distribution loop will not only improve the power consumption of the building through reduced tertiary (building) pumping power but the impact on the central distribution system and chiller efficiencies will be even greater. A degraded delta-T is almost inevitable and it can be expected to fall to about one-half to two-thirds of design at low loads (Taylor, 2002) due to various causes, such as air entering and leaving temperatures, chilled water supply temperature, type and effectiveness of flow control valves, tertiary connection configuration types and operation, coil cooling loads, air economizers, etc. However, in most variable-flow chilled water with 2-way control valve systems, the root cause of low delta-T is at coil side (Zhang, 2012), for example the geometric configuration of coil. This paper firstly discusses chilled water coil heat exchanger model results to help define methods for detecting opportunities for improved delta-T when analyzing campus building systems for performance optimization measures. Meanwhile, the author developed an effectiveness-NTU cooling coil models for a case study building containing chilled water coils with a range of design configurations to study cooling coil delta-T characteristics under various conditions in order to diagnose the low delta-T imposed on the chilled water distribution loop by the building's chilled water system under various loading conditions. The results show model-based building chilled water Loop delta-T fault diagnosis is an effective way to evaluate existing building chilled water loop delta-T performance and identify avoidable or resoluble causes for improving chilled water loop delta-T.

Key Words: chilled water loop Delta-T, chilled water coil heat exchanger model, central distribution system, variable-flow Chilled Water System, energy efficiency

1. Introduction

Improving chilled water delta-T, which is the temperature difference of chilled water supply and return temperature, in campus buildings that are connected to a central distribution loop will not only improve the power consumption of the building through reducing tertiary (building) pumping power but the impact on the central distribution system and chiller efficiencies will be even greater. However, almost every real chilled water system is plagued by low delta-T syndrome, particularly at low cooling loads. Delta-T degrading is almost inevitable can it can be expected to fall to about one-half to two thirds of design at low loads (Taylor, 2002). Many factors contribute to the loop chilled water delta-T, such as chilled water supply temperature, cooling coil air entering and leaving temperature, type of flow control valves, tertiary connection types coil cooling loads, air economizers, etc. However, in most variable-flow chilled water with 2-way control valve systems, the root cause of low delta-T is at coil side (Zhang, 2012).

Various studies have discussed how to keep a higher delta-T for chilled water systems. Taylor (2002) addressed the causes of degrading delta-T along with mitigation measures. The causes of low delta-T syndrome are broken into three categories: causes that can be avoided, causes that can be resolved but may not result in energy savings, and causes that cannot be avoided. The water laminar flow in the cooling coil is introduced in the second category. He addressed why delta-T degradation would usually occur and how to design around that eventuality to maintain chiller plant efficiency, despite a degrading delta-T. The focus was to improve chiller low load performance and try to fully load the chiller. Wang et al. (2006) studied the factors, such as cooling coil size, chilled water supply temperature, outside air flow, space cooling load, coil fouling condition, and so on, which may cause low delta-T syndrome in a district cooling system. The influences for the delta-T of these factors are compared in the simulation with the conclusion that the main cause for the low delta-T syndrome for the system in the simulation is the improper use of 3-way control valves. Fiorino(1996) recommended 25 "best practices" to achieve high chilled water delta-T ranged from component selection criteria to distribution system configuration guidelines. An example was provided that low delta-T will prevent the building's cooling from being satisfied at peak cooling load conditions. It was pointed out the chilled water delta-T in a variable flow hydronic cooling system should be equal to design at full load and greater than design at part load. Moe (2005) proposed to apply pressure independent control valves to achieve high delta-T across coils. Conventional 2-way control valves were replaced with pressure independent control valves at coils and used to control the process. This valve could eliminate the effect of sudden pressure difference variations on the coil flow rate control or authority distortion. These studies proposed various qualitative analyses to delta-T degradation based on practical observation or simplified engineering calculations. However, there is still shortage of detailed quantitative analyses on coil performance change at various operating conditions.

In this paper, the author develops a cooling coil model with design geometric configurations to study cooling coil delta-T characteristics under various conditions. The simulation results will support CC® engineers to evaluate existing building chilled water loop delta-T performance and identify avoidable or resoluble causes.

2. Energy impact of degrading Delta-T

Figure 1 shows a schema of chiller plant serving several building in a larger facility, such as a university campus. The system is piped in a typical primary-secondary manner with some tertiary pumps at remote buildings.

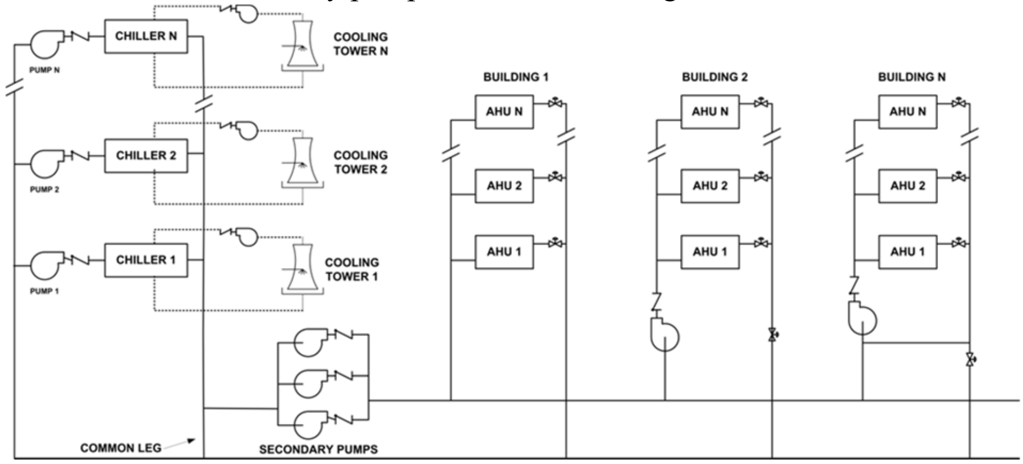

Fig. 1 Typical chilled water plant and distribution system

$$Q = m_w C_{pw}(CHWRT - CHWST) \quad (1)$$

If the delta-T in a system is low, at least two problems results: increased pump energy usage and either an increase in chiller and cooling tower energy usage or a failure to meet cooling loads. The increase in chilled water pump energy is obvious. According to Equation 1, any reduction in delta-T must cause a proportional increase in chilled water flow rate. Pump energy, theoretically, is proportional to the cube of the flow rate, so any increase in flow will have a much higher increase in pump energy. In real systems, actual pump energy impact will be less than this theoretical relationship suggests, but the impact is significant.

The impact on chiller energy usage is more complex to determine and will be a function of how the chillers are controlled. There are two basic chiller start/stop control strategies, one based on system flow rate and the other based on thermal load. Ideally, the two strategies would be effectively the same since flow and load should track in a variable-flow system. However, when flow and load do not track, when delta-T falls, neither strategy can work ideally.

The flow-based chillers strategies stage chillers and primary chilled water pumps in an attempt to keep the primary system flow larger than the secondary system flow. In this way, the secondary supply water temperature is equal to the primary water temperature leaving the chillers. When flow in the secondary exceeds the primary, another primary water pump and chiller associated cooling tower and condenser pump are started. A pump and chiller are shut off when flow in the common leg exceeds that one pump.

The load-based strategy measures system load or indirect indication of load such as return water temperature. Chillers are started when the operating chillers are operating at their maximum capacity. Chillers are stopped when the measured load is less than the operating capacity by the capacity of one chiller.

The flow-based control system will always make sure loads are met by starting additional chillers and pumps to keep the primary system flow larger than the secondary flow. But this means that chillers are not fully loaded when delta-T is below design. For example, assume the system was sized a 14°F (7.8 °C) delta-T on both the primary and secondary sides. If the system were at 50% load but the actual delta-T was only 7 °F (3.9°C), all the chillers, cooling towers, condensing pumps and primary pumps in the plant would have to operate to keep the primary flow up. This wastes pumps, chillers and other auxiliary equipment energy since the chillers would all be operating at 50% of capacity, less than the 65% to 85% range where efficiency is typically maximized for fixed speed chillers, and the other auxiliary equipment, cooling towers and condensing pumps, would all also be operating.

The load-based control system would not start a new chiller until the operating chillers were loaded. As delta-T degrades, secondary flow increases, causing water in the common leg to flow from the secondary return back into secondary pumps. This causes the secondary supply water temperature to rise, which in turn causes coil performance to degrade, which in turn causes control valves to open more to demand more flow, which in turn causes ever increasing flow in the secondary and ever warmer supply water temperatures. Eventually, coils will starve, their control valves will be wide open, and temperature control is lost. The system controlling chiller stating would be obvious to these problems; it would not start more pumps and chillers since the operating chillers were not fully loaded.

3. Cooling coil Model

Chilled water cooling coils are often fin and tube heat exchangers, which consist of rows of tubes that pass through sheets of formed fins. As the air passes through the coil and contacts the cold fin surfaces, heat transfers from the air to the chilled water flowing through the tubes. A wide range of models for heat exchangers is currently available. The effectiveness-NTU model (Braun,1989) is used in simulating the cooling coil performance. This model simulates the performance of cooling coils utilizing the effectiveness model for counter-flow geometries. The performance of multi-pass cross flow heat exchangers approaches that of counter-flow devices when the number of rows is greater than four. The minimum possible of the exit air through a cooling coil is that the exit air was saturated at a temperature equal to that of the incoming water stream. The air-side heat transfer effectiveness is defined as the ratio of the air enthalpy difference to the maximum possible air enthalpy difference if the exit air was at the minimum possible enthalpy. Assuming that the Lewis number equals one, Braun (1989) has shown that the air effectiveness can be determined using the relationships for sensible heat exchanges with modified definitions for the number of transfer units and the capacitance rate ratios. Fin efficiencies are required in order to calculate heat transfer coefficients between air stream and coil. Threlkeld(1970) notes that the performance of rectangular-plate fins of uniform thickness can be approximated by defining equivalent annulus fins. Efficiencies are calculated for annulus fins of uniform thickness ignoring end effects. Polynomial approximations are used to evaluate the

Bessel function used in calculating the efficiencies.

If the coil surface temperature at the air outlet is greater than the dew point of the incoming air, then the coil is completely dry throughout and standard heat exchanger effectiveness relationships apply.

In terms of the air-side heat transfer effectiveness, the dry coil heat transfer is

$$\dot{Q}_{dry} = \varepsilon_{dry,a}\dot{m}_a C_{pm}\,(T_{a,i} - T_{w,i}) \quad (2)$$

Where,

$$\varepsilon_{dry} = \frac{1 - \exp(-Ntu_{dry}\,(1 - C^*))}{1 - C^* \exp(-Ntu_{dry}\,(1 - C^*))}$$

$$C^* = \frac{\dot{m}_a C_{pm}}{\dot{m}_w C_{pw}}$$

$$Ntu_{dry} = \frac{UA_{dry}}{\dot{m}_a C_{pm}}$$

The airside convection coefficient is calculated using the correlations developed by Elmahdy and biggs (1979). The average heat transfer Colburn J-factor is:

$$J = C_1 {Re_a}^{C_2} \quad (3)$$

The quantities C_1 and C_2 are constant for a particular coil over the airside Reynolds number (Re_a) range of 200 to 2000.

If the coil surface temperature at the air inlet is less than the dew point of the incoming air, then the coil is completely wet and dehumidification occurs throughout the coil. For a completely wet coil, the heat transfer is

$$\dot{Q}_{wet} = \varepsilon_{wet,a}\dot{m}_a(h_{a,i} - h_{s,w,i}) \quad (4)$$

Where,

$$\varepsilon_{wet,a} = \frac{1 - \exp(-Ntu_{wet}(1 - m^*))}{1 - m^* \exp(-Ntu_{wet}(1 - m^*))}$$

$$m^* = \frac{\dot{m}_a C_s}{\dot{m}_{w,i} C_{pw}}$$

$$\mathrm{Ntu_{wet}} = \frac{\mathrm{UA_{wet}}}{\dot{m}_a}$$

UA's are normally given in terms of a temperature difference, but in this case UAwet is the heat conductance in terms of an enthalpy difference. Threlkeld (1970) gives a method for computing fin efficiencies for wet coils using the relationships available for dry coils.

Depending upon the entering conditions and flow rates, only part of the coil may be wet. A detail analysis involves determining the point in the coil at which the surface temperature equals the dew point of the entering air. In order to calculate the heat transfer through the cooling coil, the relative areas associated with the wet and dry portions of the coil must be determined Braun (1989) presents the following method for calculating the heat transfer in a partially wet coil. The fraction of the coil surface area that is dry is

$$f_{dry} = \frac{-1}{K} \ln\left[\frac{(T_{dp}-T_{w,o})+C^*\,(T_{a,i}-T_{dp})}{\left(1-\frac{K}{Ntu_0}\right)(T_{a,i}-T_{w,o})}\right] \quad (5)$$

Where,

$$K = Ntu_{dry}\ (1 - C^*)$$

The effectiveness for the wet and dry portions of the coil is

$$\varepsilon_{wet,a} = \frac{1-\exp(-(1-f_{dry})Ntu_{wet}(1-m^*))}{1-m^*\exp(-(1-f_{dry})Ntu_{wet}(1-m^*))} \quad (6)$$

$$\varepsilon_{dry,a} = \frac{1-\exp(-f_{dry}Ntu_{dry}(1-C^*))}{1-C^*\exp(-f_{dry}Ntu_{dry}(1-C^*))} \quad (7)$$

The water temperature at the point where condensation begins is

$$T_{w,x} = \frac{T_{w,i}+\frac{C^*\varepsilon_{wet,a}\left(h_{a,i}-h_{s,w,i}\right)}{c_{pm}} - C^*\varepsilon_{wet,a}\varepsilon_{dry,a}T_{a,i}}{(1-C^*\,\varepsilon_{wet,a}\varepsilon_{dry,a})} \quad (8)$$

The exit water temperature is

$$T_{w,o} = C^*\varepsilon_{dry,a}T_{a,i} + (1 - C^*\varepsilon_{dry,a})T_{w,x} \quad (9)$$

The water side heat transfer coefficient is determined using standard turbulent flow relations in effectiveness-NTU model (Braun,1989). The most commonly used one for fully developed turbulent flow inside smooth round tubes is the Dittus-Boelter correlation (Dittus and Boelter 1930).

The Effectiveness-NTU coil model is a forward cooling coil model calculates the coil cooling capacity from the entering air and water flow rates and temperatures. However, the real control logic is to determine the sole chilled water flow rate at give air discharging dry-bulb temperature set point. The corresponding chilled water leaving temperature will be calculated from the energy conservation principle.

4. Case study building

The case study building, pictured below in Figure 1, was constructed in 1990 and is located on the west campus of Texas A&M University in College Station, Texas, US (see Figure 1 below). It consists primarily of laboratories and offices, with a few classrooms, a dining center, a computer lab, and other miscellaneous spaces. The building has four floors for a total area of 166,079 square feet (14,947m^2).

Fig. 2. Case study building

The chilled water system in the building utilizes two 20 hp, 840 gpm (190 m^3/hr) chilled water pumps, with VFDs under EMCS control, and operates on a lead/lag schedule. The chilled water pumps and the related building return valve were controlled to maintain the minimum of three end loop DPs at its set point.

The HVAC system in the building consists of eight single-duct, variable air volume (VAV) air handling units (AHUs) and two small constant volume air handling units. All air handling units, pumps and terminal boxes are operated by Siemens DDC controls system. The total design maximum supply flow in the building is 201,670 cfm (95,179 L/s), of which by design a minimum of 161,400 cfm (76,409 L/s) is outside air. The design information of chilled water coils are presented in table 1

Table 1 Chilled water coils design information (IP and SI)

Unit	Service	Supply cfm	Min Outside Air cfm	Max Outside Air cfm	Design Area SQFT	ENT. Air		LVG. Air		FIN /IN
						D.B °F	W.B °F	D.B °F	W.B °F	
AHU L1	LABS	44,500	44,500	44,500	90	96	76	50.7	50.7	14
AHU L2	LABS	45,000	45,000	45,000	90	96	76	50.9	50.9	14
AHU L3	LABS	45,000	45,000	45,000	90	96	76	50.7	50.7	14
AHU L4	ANIMAL ROOM	11,760	11,760	11,760	29.4	96	76	50.4	50.4	14
AHU LS	SEMINAR	4,500	1,310	4,500	11.5	83.8	69	50.7	50.7	8
AHU LB	BOOKSTORE	4,650	460	4,650	11.5	79.8	63.8	50.8	50.5	8
AHU LC	COPYSTORE	4,300	430	4,300	11.5	79.8	63.8	50.7	50.5	8
AHU LD	DINING	14,160	7,840	14,160	29.4	89.4	71.5	50.5	50.5	14
AHU LO	OFFICES	19,000	5,600	19,000	42.8	83.3	66.8	51.8	51.5	8
AHU SG	SWITCHGEAR	8,800	0	8,800	20.4	90	72	52.5	52.5	14

Unit	Service	Supply L/s	Min Outside Air L/s	Max Outside Air L/s	Design Area m^2	ENT. Air		LVG. Air		FIN /cm
						D.B °C	W.B °C	D.B °C	W.B °C	
AHU L1	LABS	21,002	21,002	21,002	8.36	35.6	24.4	10.4	10.4	5.5
AHU L2	LABS	21,238	21,238	21,238	8.36	35.6	24.4	10.5	10.5	5.5
AHU L3	LABS	21,238	21,238	21,238	8.36	35.6	24.4	10.4	10.4	5.5
AHU L4	ANIMAL ROOM	5,550	5,550	5,550	2.73	35.6	24.4	10.2	10.2	5.5
AHU LS	SEMINAR	2,124	618	2,124	1.07	28.8	20.6	10.4	10.4	3.1
AHU LB	BOOKSTORE	2,195	217	2,195	1.07	26.6	17.7	10.4	10.3	3.1
AHU LC	COPYSTORE	2,029	203	2,029	1.07	26.6	17.7	10.4	10.3	3.1
AHU LD	DINING	6,683	3,700	6,683	2.73	31.9	21.9	10.3	10.3	5.5
AHU LO	OFFICES	8,967	2,643	8,967	3.98	28.5	19.3	11.0	10.8	3.1
AHU SG	SWITCHGEAR	4,153	-	4,153	1.90	32.2	22.2	11.4	11.4	5.5

The eight AHUs are grouped into two types: Lab AHUs and office AHUs. The lab AHUs are 100% OA, while office AHUs minimum outside airflow is about 30% of total supply airflow. The AHU L2 and AHU O are selected as representative of lab AHU and office AHU respectively. The cooling coil geometry configuration is the inherent factor determining the coil delta-T characteristics. The geometry parameters of AHU L2 and AHU O are presented in table 2

Table 2 Geometry parameters of AHU L2 and AHU O (IP and SI units)

No	Parameters	AHU L2		AHU O	
		IP	SI	IP	SI

1	Width	130	inch	330.2	cm	102	inch	259.1	cm
2	Height	90	inch	228.6	cm	55	inch	139.7	cm
3	Number of rows	8				6			
4	Tube outside diameter	0.5	inch	1.3	cm	0.5	inch	1.3	cm
5	Tube inside diameter	0.45	inch	1.1	cm	0.45	inch	1.1	cm
6	Tube material	copper				copper			
7	Fin	14	Fin/Inch	5.5	Fin/cm	10	Fin/Inch	3.9	Fin/cm
8	Fin thickness	0.008	inch	0.02	cm	0.008	inch	0.02	cm
9	Fin material	Aluminum				Aluminum			cm
10	Tubes distance (perpendicular to air flow)	1.25	inch	3.2	cm	1.25	inch	3.2	cm
11	Tube Spacing (Parallel to air flow)	1	inch	2.5	cm	1.25	inch	3.2	cm

5. Model Calibration

The two cooling coil models are calibrated by design performance data and field measure data. The supply air flow, air temperature and relative humidity before and after cooling coils, chilled water supply and return temperatures of AHU L2 were trended for every 15 minutes. Since the AHU O has no flow station, the coil design performance data and field snapshot measured data are used to calibrate AHU O model. The measured and simulated chilled water delta-T for AHU L2 and AHU O are presented in Figure 2 and Figure 3. The cooling coil design performance and field measurement data of AHU O are shown in table 3.

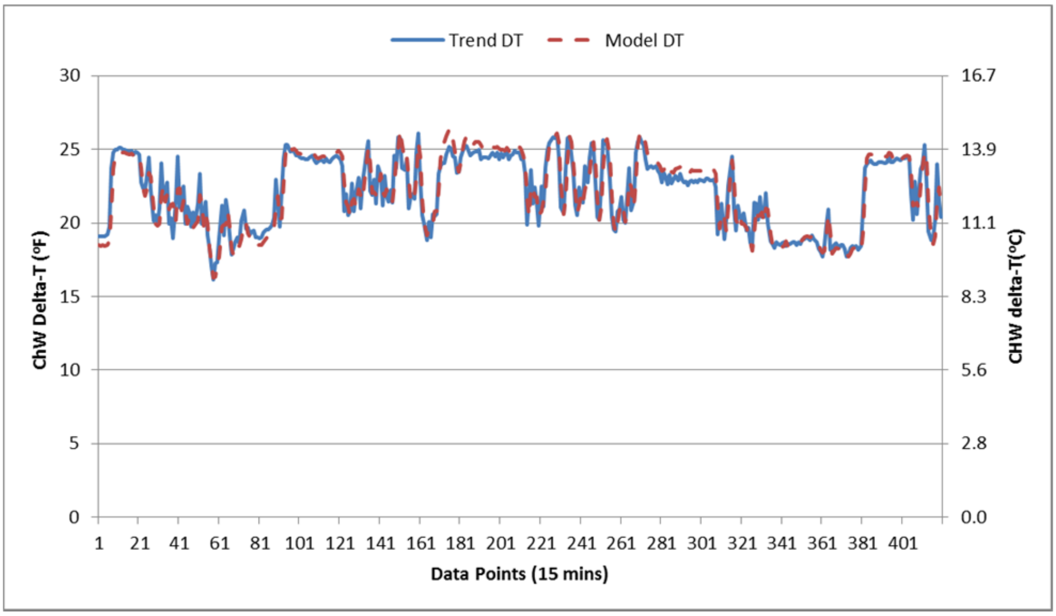

Fig. 3 AHU L2 chilled water delta-T(Model Vs. Trending)

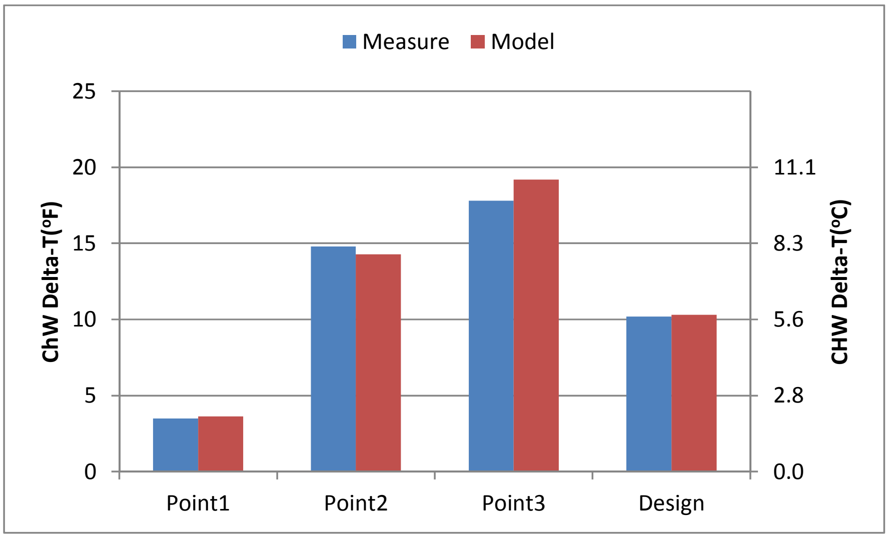

Fig. 4 AHU O chilled water delta-T (IP and SI units)

Table 3 AHU O chilled water calibration results (IP and SI units)

AHU O	Air Side					Waterside			Measure Delta-T	Model Delta-T	Error
	flow	Before		After coil		Supply	Return	flow			
IP	CFM	T (°F)	RH (%)	T (°F)	RH (%)	T (°F)	T (°F)	GPM	°F	°F	%
1	6,450	74.9	61.6%	45.6	89%	42.8	46.3	224	3.5	3.6	3%
2	6,450	97.1	26%	50.8	95%	42.8	57.6	55	14.8	14.3	-4%
3	6,450	97.9	25%	55.5	97%	42.8	60.6	35	17.8	19.2	8%
Design	19,000	83.3	42%	51.7	94%	44	54.2	177	10.2	10.3	1%
SI	L/s	T (°C)	RH (%)	T (°C)	RH (%)	T (°C)	RH (%)	L/s	°C	°C	%
1	6,450	74.9	61.6%	45.6	89%	42.8	46.3	224	3.5	3.6	3%
2	6,450	97.1	26%	50.8	95%	42.8	57.6	55	14.8	14.3	-4%
3	6,450	97.9	25%	55.5	97%	42.8	60.6	35	17.8	19.2	8%
Design	19,000	83.3	42%	51.7	94%	44	54.2	177	10.2	10.3	1%

Both AHU L2 and AHU O models show a good agreement with measured data. There is 1% error in design condition. The CV(RMSE) is 6% for AHU O model. AHU L2 model underestimates the dynamic character of coil performance in some points between point 25 and 50, but the overall trend of calculation results agree with the measure data. The AHU L2 model CV(RMSE) error is 2.9%.

6. Building chilled water Loop Delat-T fault Diagnosis

The building chilled water loop delta-T versus cooling load tonnage and outside air temperature is presented in figure 4 and figure 5.

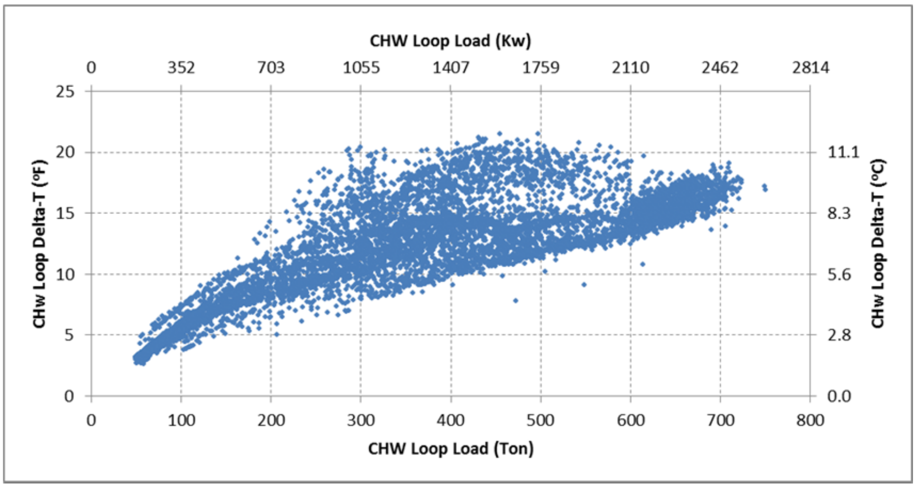

Fig. 5. Chilled water loop Delta-T Vs. cooling load (IP and SI units)

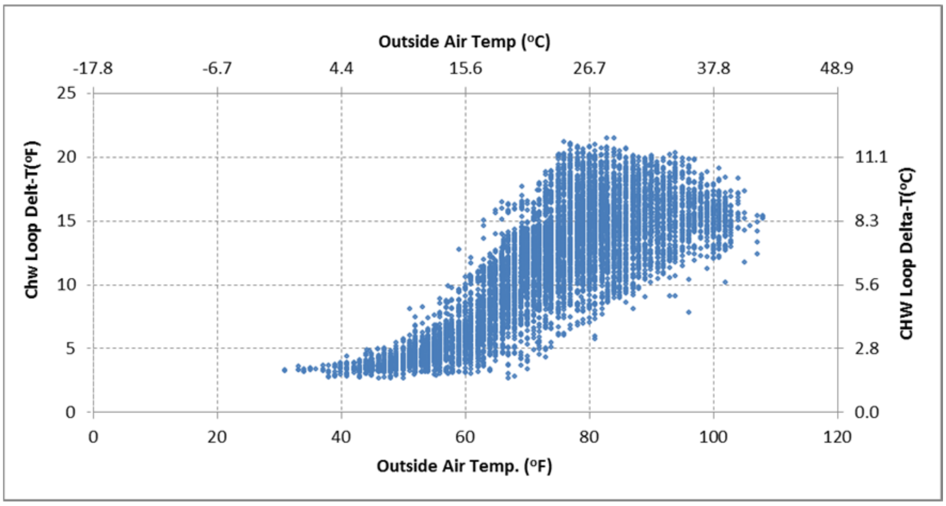

Fig. 6. Chilled water loop Delta-T Vs. outside air temperature (IP and SI units)

The maximum value of existing building chilled water loop delta-T is about 22 °F (12.2°C), while the minimum chilled water loop delta-T is only about 3°F. The design delta-T of cooling coils is 16°F (8.9°C) and 10°F (5.6°C) for Lab AHU and Office AHU respectively. The chilled water loop delta-T can be affected by various causes, such as air entering and leaving temperatures, chilled water supply temperature, type and effectiveness of flow control valves, coil cooling loads and air economizers, etc. Therefore, it is a big challenge for CC engineers to evaluate the chilled water loop delta-T performance and identify opportunities to improve chilled water loop delta-T without a model supported. A calibrated cooling coil model will be a very useful tool to predict the ideal chilled water loop delta pattern versus cooling load or outside air temperature under different scenario.

The airside and water side conditions are the extrinsic factors determining the cooling coil delta-T. In this study, the dry bulb temperature of weather data are divided into 33 bins (40°F ~104°F, 4.4°C ~40°C) and the average dry-bulb and wet bulb temperatures in each dry-blub bin are calculated and used as the outside air temperature profiles. The average chilled water supply temperature in each dry-blub bin is used as the chilled water supply temperature. The space cooling and heating set points are 70°F(21.1°C) and 75°F(23.9°C) respectively. The mixed air temperatures of office AHU are calculated based on outside air temperature, return air temperature and outside air percentage. Each type AHU is calculated under three different supply air flow: minimum, average and maximum. The air flow ratios for office AHU are 30%, 60% and 80% of the design airflow (19,000CFM, 8,967L/s) and for lab AHU are 60%, 70% and 90 % of the design airflow (21,237CFM,).

At the beginning of the fault diagnosis, the measured building chilled water loop delta-T is compared with the simulated cooling coil chilled water delta-T of office and Lab AHU as a function of outside air temperature with different supply airflow, when the cold deck temperature is maintained at normal set point 55°F(12.8°C).

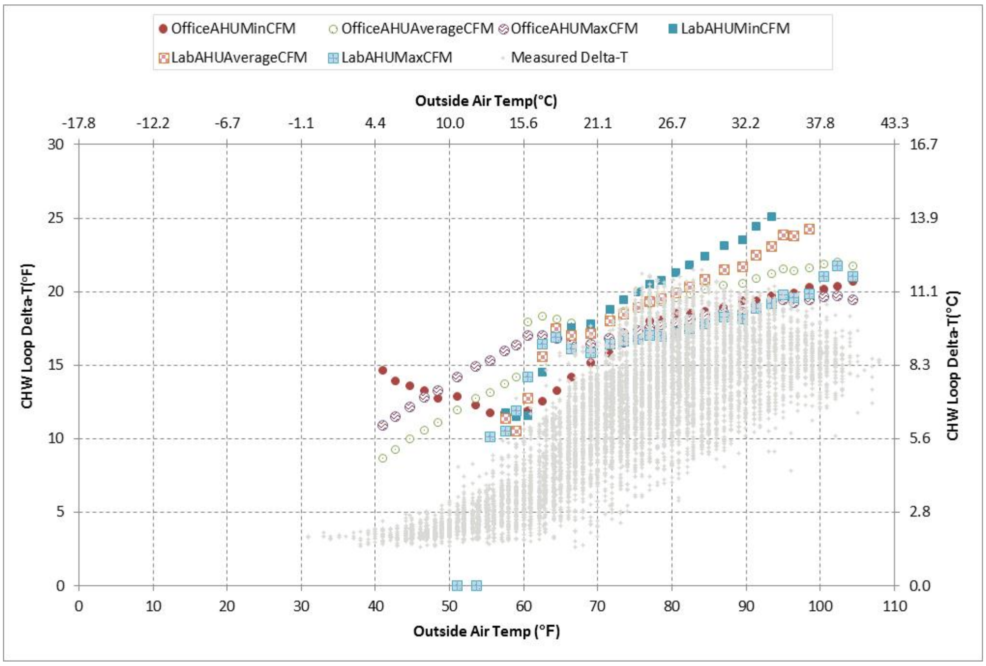

Fig. 7 Measured and simulated chilled water Delta-T

(Cold deck temp. 55°F, 12.8°C, IP and SI units)

It clearly shows the simulated cooling coil chilled water delta-T for both types AHU is higher than measured chilled water loop DT for most of the points. It indicates that there is a good opportunity to improve this building chilled water loop delta-T. It also illustrates that, the chilled water delta-T does not always increase with outside air temperature increase. When the office AHU airflow is minimum, the chilled water delta-T decreases from 14.7°F (8.2°C) to 11.9°F(6.6°C) as the outside air temperature increases from 40°F(4.4°C) to 60°F(15.6°C), then it is rising with outside air temperature increasing. With the load decreasing, the significant increase in water film resistance at low flows would still support the notion that delta-T in the laminar flow region should fall. But there is another factor occurring at the same time that more than offsets this rise in heat transfer resistance: the low flow rate through the coil effectively “sees” an oversized coil, a large amount of heat transfer area relative to the amount of water running through the coil. The water stays in the coil longer and more heat is transferred, which causes the temperature to increase rather than decrease. The chilled water delta-T will be the worst case if chilled water valve is fully open. Figure 7 presents the simulated results when chilled water valve is fully open.

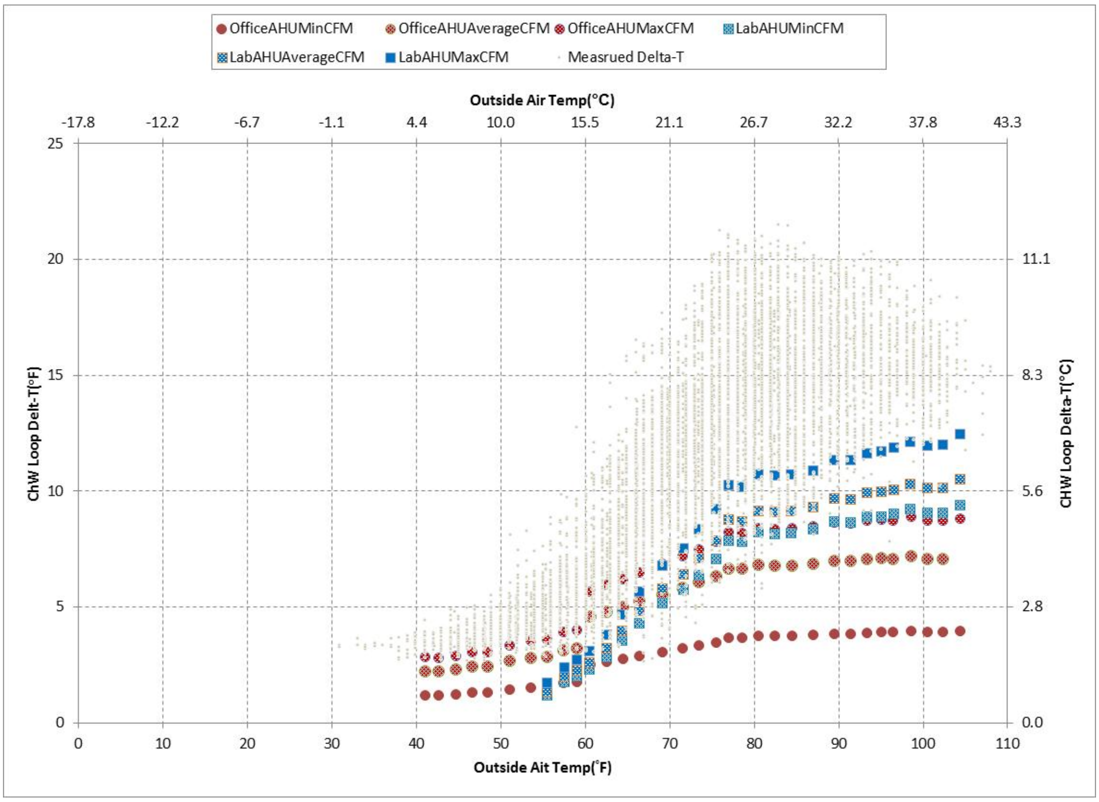

Fig. 8 Measured and simulated chilled water Delta-T

(Chilled water valve fully open, IP and SI units)

The most measured chilled water loop delta-T points are above the worst case points. It illustrates the chilled water loop is under control and the most chilled water values of AHUs are working properly. There is no significant leakage by valves or other mechanical issues on chilled water control valves.

Figure 8 presents the comparison result between the measured building chilled water loop delta-T and simulated cooling coil chilled water delta-T of office and Lab AHUs when the cold deck temperature is maintained at 50°F(10°C).

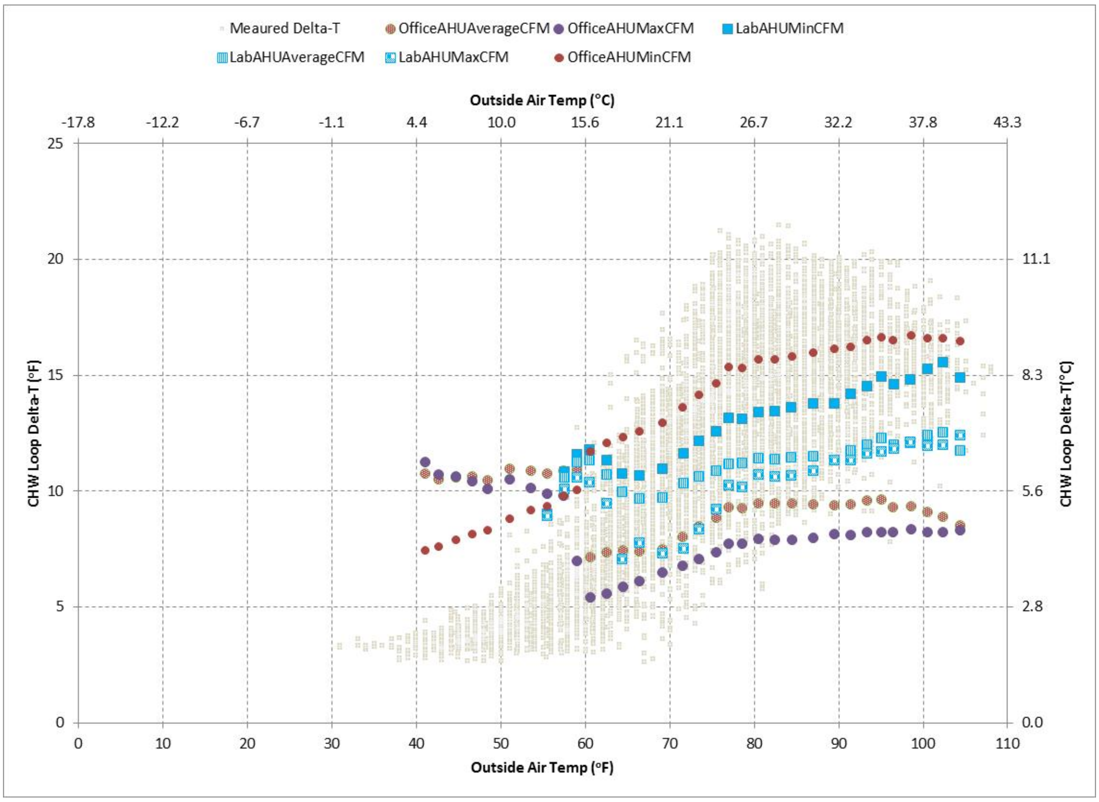

Fig. 9 Measured and simulated chilled water Delta-T

(Cold deck temp. 50°F, IP and SI units)

At this scenario, it is observed that considerable measured chilled water delta-T points are higher than the simulated chilled water delta-T when outside air temperature is higher than 70°F (21.1°C), while measured chilled water delta-T points are lower than simulated chilled water delta-T when outside air temperature is less than 60°F (15.6°C). The results of Figure 6 and Figure 8 indicate that the actual average cold deck air temperature set point is between 50 °F (10°C) and 55°F (12.8°C). The bigger overlap region between measurement and simulated points of figure 8, indicates cold deck air temperature is at cold side. Hence, the building chilled water loop delta-T can be increased by optimizing cold deck air temperature set point.

However, when outside air temperature is less than 55 °F (12.8°C), the measured chilled water delta-T is still significantly lower than simulated value even when the cold deck air temperature is 50°F(10°C). A further analysis is conducted to identify the possible reasons which cause a lower chilled water delta-T at lower outside air temperature condition. When outside air temperature is less than 55°F (12.8°C),, the office AHUs chilled water delta-T will dominate the whole building chilled water loop delta-T.As the lab AHUs are 100% OA, its cooling load will be very low when outside air temperature is cool. Hence, only the office type AHU is simulated to study the low chilled water delta-T issues when outside air temperature is cool. Figure 9 presents office AHU chilled water delta-T pattern versus outside air temperature with and without economizer.

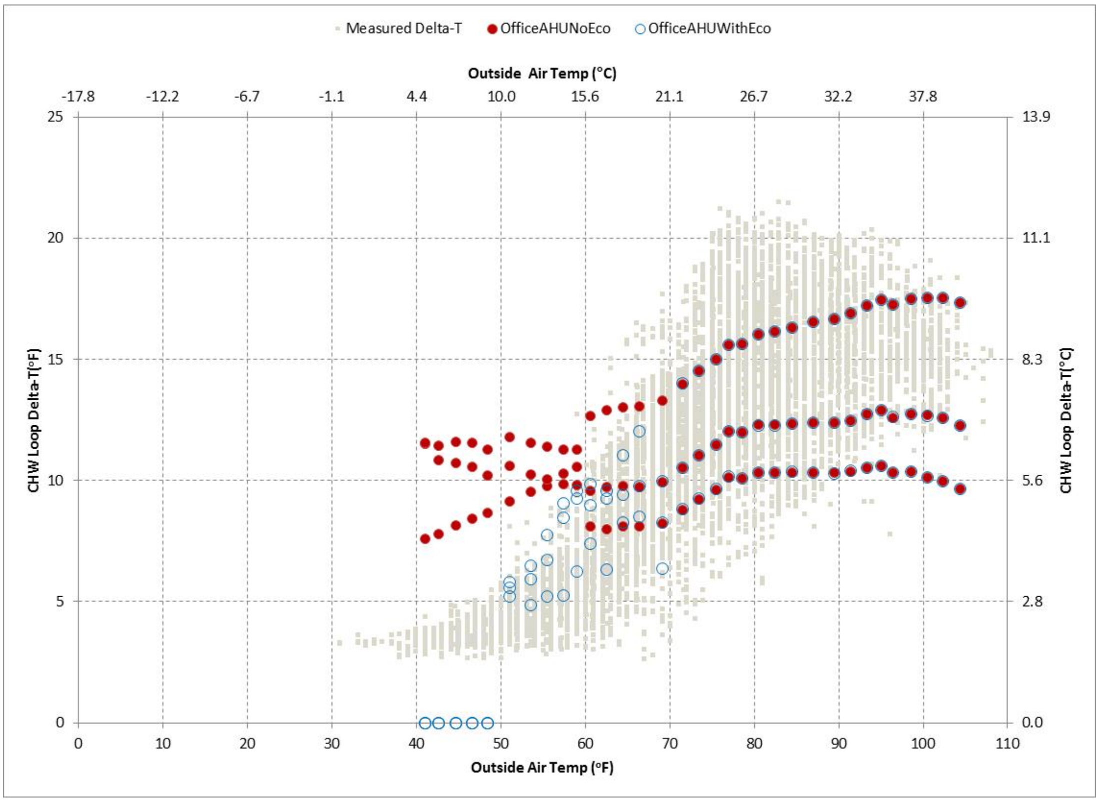

Fig. 10 Office AHU w/o Economizer cold deck air temperature at 50 °F

When an airside economizer is applied, the mixed temperature of outside air and return air or the coil entering temperature is lower than the case without an economizer, which results on a lower chilled water delta-T. When the outside air is cool enough, the mixing temperature drops below the coil discharging set point and there is little cooling on the coil. In real situation, when the coil control valve cannot precisely modulate the chilled water flow, the leaking chilled water will over-cool the air and lead to a lower-than-simulated delta-T. The measured chilled loop delta-T appears this phenomenon that may explain why the measured delta-T is lower than the simulated delta-T when outside air temperature is lower. The water loop pressure fluctuation may also push more water through the control valve and decrease the return water temperature further; however, this issue cannot be identified by simulation model, the field investigation is necessary to further identify these types of issues.

7. Summary

Improving chilled water delta-T in campus buildings that are connected to a central distribution loop will not only improve the power consumption of the building through reducing tertiary (building) pumping power but the impact on the central distribution system and chiller efficiencies may be even greater. However, almost every chilled water system encountered by the authors suffers from low delta-T, particularly at low cooling loads. It is a big challenge for CC engineers to quickly evaluate the chilled water loop delta-T performance and identify potential measures to improve chilled water loop delta-T. Understanding the coil delta-T performance characteristics is a critical step toward identifying possible measures to improve chilled water loop delta-T. This paper demonstrated a building chilled water Loop delta-T fault diagnosis procedure using a case study building as an example. In this procedure, the effectiveness-NTU coil model is employed to model the coil chilled water leaving temperature at given airside and waterside conditions. Both AHU L2 and AHU O models show a good agreement with measured data. The models CV(RMSE) are 6% and 2.9% for AHU O and AHU L2 respectively. According to the above analysis, the following conclusions for the case study building can be drawn:

- Based on simulation results, there is a good potential to improve the case study building's chilled water delta-T.
- The lower discharge air temperature set point is the main avoidable cause of low chilled water delta-T for the case study building. Optimizing cold deck air temperature set point could improve the chilled water loop delta-T.
- Economizer contributes to low chilled water delta-T during cool season.
- The chilled water laminar flow in the cooling coil is not a major cause for cooling coil lower delta-T
- Although the chilled water valves in general appear to be operating properly, the measured chilled water delta-T being lower than simulated delta-T in low load period indicates that a few of the chilled water valves may be leaking by or the coil control valves may not precisely modulate the chilled water flow. Whether leaking or poorly controlling air temperature, a lower-than-expected leaving air temperature will lead to a lower-than-simulated delta-T.

It should be noticed that when a very low cooling load is on the coil, the theoretical chilled water flow is very low and the simulation results may become unreliable. In addition, the possible cause of low chilled water delta-T varies from building to building. Hence, the intent of calibrated cooling model is not to identify all possible causes of low chilled water delta-T, but it can provide a benchmark for cooling coil delta-T performance. In turn, it can help CC engineers to better evaluate current chilled water delta-T performance and provide some clues to find possible solutions to improving chilled water loop delta-T.

NOMENCLATURE

C_{pm} = constant pressure specific heat of moist air
C_{pw} = constant pressure specific heat of liquid water
CHWRT= chilled water return temperature
CHWST= chilled water supply temperature
C_s = average slope of saturation air enthalpy versus temperature
C^* = ratio of air to water capacitance rate for dry analysis (maCpm/mwCpw)
C1, C2 = coefficient
h_a = enthalpy of moist air per mass of dry air

h_s = enthalpy of saturated air per mass of dry air
m_a = mass flow rate of dry air
m_w = mass flow rate of water
NTU = overall number of transfer units
Q = overall heat transfer rate
T_a = air temperature
T_{dp} = air dew point temperature
T_s = surface temperature
T_w =water temperature
UA =overall heat conductance
a =air humidity ratio
ω_s =humidity of saturated air

SUBSCRIPTS
a =air stream conditions
dry =dry surface
e =effective
i =inlet or inside conditions
o =outlet or outside conditions
s =surface conditions
w =water stream conditions
wet =wet surface
x =point on coil where condensation begins

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Understanding and Improving Household Energy Consumption and Carbon Emissions Policies – A System Dynamics Approach

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Abstract:
The purpose of this paper is to propose and demonstrate the application of system dynamics modeling approach to analyze and study the behavior the complex interrelationships among the different policies/interventions aimed at reducing household energy consumption and CO_2 emissions (HECCE) based on the Climate Change Act of 2008 of the UK government. The paper uses the system dynamics as both the methodology and tool to model the policies/interventions regarding HECCE. The model so developed shows the complex interrelationships among the different policies/interventions variables and presents the basis for simulating the different scenarios of household energy consumption reduction strategies. The paper concludes that the model is capable of adding to the understanding of the complex system under which HECCE operate and improve it accordingly by studying the behavior of each policy/intervention over time. The outcomes of the research will help decision makers draw more realistic policies/interventions for household energy consumption which is critical to the CO_2 emissions reductions agenda of the government.

Keywords:
CO_2 emissions, domestic buildings, household energy consumption, government policies, system dynamics.

1. Introduction

There have been concerns over sustainability issues around the world, especially when it comes to the way energy is used and the corresponding environmental impacts in the form of climate change, global warming, etc. The effects of climate change, due to carbon dioxide and other greenhouse gas emissions for example, could see the global temperatures rise by up to 6^{o}C (UNDESA, 2010) thereby causing extremes in weather systems. Reduction in energy consumption patterns in dwellings is, therefore, seen as one of the breakthroughs to curtail this threat. According to the Office of National Statistics (2009), total energy consumption in buildings in the UK accounts for 42.3% in relation to the UK total energy consumption. 27.5% of this amount was consumed in domestic buildings in the year 2008. Presently, CO_2 emissions attributed to domestic buildings alone is around 26% of the total UK's carbon emissions (Natarajan *et al.*, 2011). For this reason, the domestic sector of the UK's economy is then chosen as the centre of focus for both mitigation and adaptation agendas (Natarajan *et al.*, 2011) with a view to meeting the CO_2 emissions reductions target of 80% by 2050 based on 1990 levels as laid down by the Climate Change Act of 2008.

To have this target met, the UK's government has initiated a number of policies/strategies like fabric insulation improvement, energy tariffs, alternative energy sources e.g. micro-generation, energy subsidy for uptake of technology like micro-generation, behavioral change, initiatives on fuel poverty, *e.t.c.* to serve as measures against this menace. Oladokun *et al.* (2012) argues that the issue of sustainability in terms of HECCE is a complex socio-technical system that must be acknowledged as such and appropriately understood as a system because the characteristics of the parts making up this system cannot be viewed individually. Prior now, there have been a plethora of approaches used in analyzing the HECCE. The reality on ground suggests that there still remains debate on how best energy consumption and carbon emissions reductions in dwellings can be achieved when there are different policies evolving on a daily basis! It is against this backdrop that this paper intends to propose and demonstrate a methodology that is capable of modeling the complex system of different policies regarding HECCE. This study will contribute to the body of knowledge by adding to the understanding of the complex nature of HECCE and providing a model of interrelationships/dependencies among different variables that need consideration when analyzing and formulating policies regarding HECCE. Further, the study would contribute to the body of knowledge by providing a reliable tool that may even serve as learning laboratory for policy/decision makers to test different policies and answer the question of “what if” of carbon reductions strategies.

2. The Epistemology of Household Energy Consumption and CO_2 Emissions Models

In energy studies literature, there has been a superfluity of frameworks serving as theoretical knowledge-base to conceptualize HECCE and these have contributed in no small measure to the tools for the analysis and policy formulation regarding HECCE. Keirstead (2006) argues that these frameworks fall within two domains – disciplinary and integrated domains.

2.1. Disciplinary Frameworks

For years, “disciplinary” frameworks have been the dominant guiding approach for explanation and policy making regarding HECCE. For example, these frameworks are developed from four major disciplines with each discipline illustrating its own approach/framework for solving HECCE problems. These disciplines are engineering, economics, psychology, and sociology and anthropology. Engineering frameworks, for example, illustrates mainly the technology of HECCE by estimating HECCE based on the physical laws with little or no attention to economic, sociology, or even behavioral aspects of HECCE (*i.e.* the studies of Anderson, 1985; Stokes *et al.*, 2004; Hart and Dear, 2004). The economic framework as one of the disciplinary frameworks conceptualizes HECCE when it comes to understanding HECCE due to the effects of income levels, energy prices and taxes, *etc* (Ruffell, 1977; Baker, 1991; Greening *et al.*, 1995; Ironmonger *et al.*, 1995). As a social science based framework, however, it introduces some behavioral aspects.

Interestingly, Wheelock and Oughton (1994) argue based on the available evidence that the concept depicts by economic approach is not complete in aiding the understanding of HECCE. It is against this background that the studies in the area of psychology took up this challenge and contribute to the understanding of household energy consumption behavior. Notably in this circle is the Theory of Planned Behavior (TPB) of Ajzen (1991), which immensely contributed to the behavioral aspect of HECCE by serving as theoretical knowledge-base to many studies. However, the TPB framework cannot be used as a standalone framework for explaining HECCE because the theory only used personal constructs like attitudes and beliefs without any recourse to other aspects like social and cultural contexts. This then led to studies in the field of sociology and anthropology in a bid to conceptualize energy and society.

Reflecting on all these approaches, it is evident that they are unlikely to capture the kind of complex problems plaguing energy sector now and hence the need for a more robust approach capable of integrating a number of disciplinary approaches together. It is on the basis of this that a small number of literatures suggest "integrated" frameworks that cut across many disciplines.

2.2. Integrated Frameworks

A number of "integrated" frameworks have been used to conceptualize HECCE in order to aid a better understanding of energy issue and proffer adequate solutions. The study of van Raaij and Verhallan (1983) provided a novel approach to conceptualizing energy behavior. His framework made use of both physical parameters of the dwellings and behavioral characteristics of the households. The research of Lutzenhiser (1992) proposes a cultural framework of HECCE and the work of Wilk (2002) gives the global consumption framework of household energy consumption. The study of Hitchcock (1993) uses the systems theory to provide an integrated framework of energy use and behavior in domestic buildings and argues that energy consumption patterns in domestic buildings needs to be fully understood from systems perspective. The study used the concept of socio-technical systems to conceptualize HECCE and came up with a framework. However, no modeling technique was proposed to capture these socio-technical systems. It is then pertinent to look at the modeling approaches of these "integrated" frameworks.

2.3. Bottom-Up and Top-Down Modeling Approaches

Over the years, there have been a number of studies on modeling approaches to capture domestic energy consumption (Strachan and Kannan, 2008; Bohringer and Rutherford, 2009; Tuladhar *et al.*, 2009; Swan and Ugursal, 2009); Kavgic *et al.*, 2010). Based on Kavgic (2010), these approaches vary tremendously in terms of requirements, assumptions made, and the predictive abilities of the models. Majority of the studies (Kavgic *et al.*, 2010; Kelly, 2011) argue that there are basically two epistemic approaches to modeling HECCE. According to Kavgic *et al.* (2010) and Kelly (2011), these approaches are either top-down approach or bottom-up approach. They acknowledged that there have been some cases where a hybrid of the two approaches have been made which combined them together to form more robust models.

These approaches have received one form of criticism or the other when it comes to modeling HECCE. Among those that have offered criticism is Natarajan et al. (2011). This came from the point of view that the issue of energy consumption is a complex one which needs to be acknowledged as such by looking at it from the non-deterministic perspective rather than the deterministic approach being currently in use. Also, majority of these modeling approaches find it difficult to model a combination of quantitative and qualitative variables together. This difficulty stems from the fact that the issue of energy consumption and carbon emissions in general involves a web of interaction between householders and the technology put in place in the dwellings and the wider socio-economic environment. This then calls for an approach that is able to cope with this kind of difficulty. The next section then discusses system dynamics as an alternative approach to model complex systems.

3. System Dynamics – An Approach to Model Complex Systems

System dynamics (SD) has been depicted as an emerging field in the study and analysis of complex systems. It is, indeed, a multi-disciplinary subject that deals with the study of any dynamic system. Motawa and Banfill (2010) argue that SD is both a methodological approach and set of analytical tool capable of palliating the deficiencies of traditional analytical approach and the justification for this modeling paradigm has been covered elsewhere by the authors (Oladokun *et al.*, 2012). There are quite a number of definitions of SD, but the one given by Coyle (1997) offers a more robust definition as an approach that "deals with the time-dependent behavior of managed systems with the aim of describing the system and understanding, through qualitative and quantitative models, how information feedback governs its behavior, and designing robust information feedback structures and control policies through simulation and optimization". Fundamentally, SD deals with 'feedback' processes (as given in the definition) and built on 'cause and effect' relations among different variables influencing the system under investigation (Ranganath and Rodrigues, 2008). According to Sterman (2000), SD is a "method to enhance learning in complex systems" as it is grounded in the theory of modern feedback control and nonlinear dynamics. This has now been applied to numerous fields of study. Sterman (2000) argues that SD has found application in modeling human behavior as well as physical and technical systems, which is capable of solving important real life problems mainly because it draws on cognitive and social psychology, economics, and other social sciences.

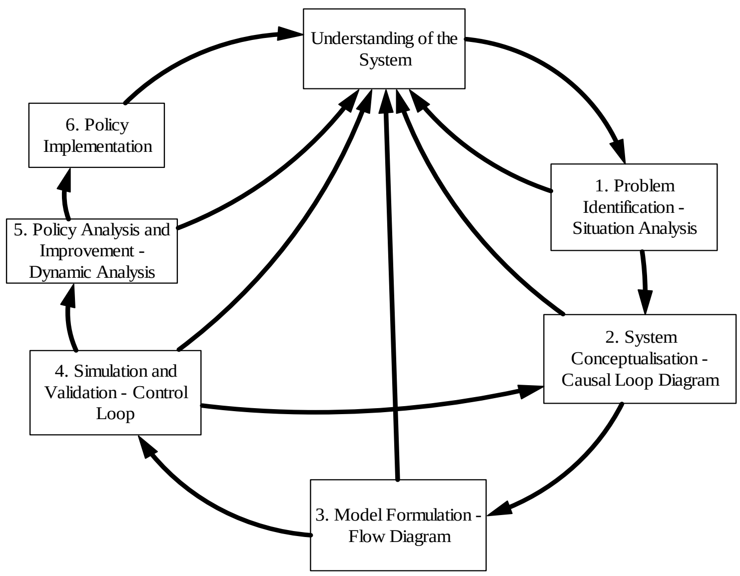

Fig. 1. System Dynamics Methodology (Adapted from Ranganath and Rodrigues, 2008)

The diagram shown in Figure 1 depicts the system dynamics methodology in a general sense as adapted from the work of Ranganath and Rodrigues (2008). This shows the method used in solving any system dynamics problem. The stages involved are interrelated and linked together as all the steps are directed towards the 'understanding of the system'. This reveals that at any point in time in each stage of system dynamics, a better insight into the problem is gotten, which eventually leads into the better understanding of the system under study. The methodology indicates that the first stage it to identify the problem in question and properly define it through the situation analysis. This involves identifying the variables in the problem and relates them to one another in order to find out the causal relationships and feedbacks in the system. Based on Ranganath and Rodrigues (2008), the most important aspect of problem identification is to identify the time-based policy parameters, which influence the dynamics of the system under study.

The second stage as shown in Figure 1 is the system conceptualization. This involves representing the 'cause and effect' relationship between the variables in the system pictorially and this is called causal loop diagram (CLD). It is worth mentioning that at this stage the diagram does not indicate the stock or the flow but merely indicates the influence of one variable on the other. Stage three involves formulating the model by representing the model using the stock and flow diagram (SFD). This diagram is a pictorial representation of the behavior of the system in the form of accumulation (stock) and flow (rate). This automatically leads to stage four where the SFD is turned into a simulation model. It must be emphasized that mere CLD or SFD do not constitute the system dynamics. It is when the variables in the model are related together in terms of equations before it can be said that it forms the simulation model. Once the model is validated accordingly, the simulation is then run and the output of the simulation is presented in the form of graphs. These graphs reveal the pattern exhibit by the variables under study over a period of time. Based on these outputs, policy analysis and improvement is carried out by the decision makers and this is stage five of the methodology. Implementation of the policy improvement (stage six) then concludes the system dynamics methodology.

This method demonstrates system dynamics as a powerful analysis tool for use by decision makers. It is worth mentioning that system dynamics has the ability to be used as a learning laboratory tool (Rodrigues and Bowers, 1996) and in conjunction with other traditional decision making techniques. The following section presents the application of system dynamics methodology to model the impact of different UK government policies on HECCE.

4. Application of System Dynamics Methodology to the Impact of Different Policies on Household Energy Consumption and CO_2 Emissions

Based on the system dynamics methodology discussed above, the following sub-sections then discuss the system dynamics steps that are covered so far in this paper.

4.1.1. Problem Identification

In system dynamics modeling process, the first step, as advocated in Section 3 above is to identify the problem that necessitates the model. The problem under study has, therefore, been explicitly discussed in Section 1 of this paper.

4.1.2. System Conceptualization

As previously highlighted, the government of the UK is taking a number of pragmatic steps in order to meet the energy consumption and carbon emission reductions targets. Among the measures on ground are: improving household fabric energy efficiency, encouragement of micro-generation of energy at household level, provision of subsidy/financial incentives for uptake of this micro-generation technology by householders, householders behavioral change, and the likes. After the review of relevant literature including government documentations was carried out in order to identify the variables to be included in the model, the system conceptualization was conducted that involves identifying the sub-systems, the model boundary, the reference modes, and the main CLD for the model. The following sub-sections then discuss these steps.

4.1.2.1. Model Sub-systems

The system under study has a number of sub-systems and each of them is controlled by a number of variables as identified from the literature. The sub-systems in this model are discussed as follows.

1. Energy efficiency of dwellings is one of the sub-systems under consideration by this model. It needs to state that the government policy on dwellings' energy efficiency aims at providing zero carbon homes which is a step towards the carbon reductions targets. This policy targets dwellings in general. Householders are required to increase the energy efficiency of their homes by improving on fabrics insulation. This may mean taking the step of cavity wall, loft, and floor insulation, drought proofing and an uptake of double glazing. This will allow the householders to spend little in heating up their homes without being in fuel poverty. Fuel poverty means "being unable to afford to keep warm". According to Department of Energy and Climate Change (DECC) (2012a), a household is considered to be in fuel poverty if it spends more than 10% of its income on fuel in order to adequately heat its home. Fuel poverty negatively affects people's health especially the elderly, children and those with a prolonged illness or disability. Poor home energy efficiency, high energy tariff and low household income have been attributed to the cause of fuel poverty.

2. Uptake of alternative energy source, in the form of micro-generation, is another sub-system that is worth discussing. Micro-generation is defined under the Energy Act 2004 and according to DECC (2012b) to be "a term used for the generation of low, zero carbon or renewable energy at a 'micro' scale". This covers any energy generation that is decentralized. Micro-generation technologies may take the form of solar photovoltaic (PV), micro-wind turbines, micro-hydro or even micro-combined heat and power (CHP). Micro-generation provides energy security by increasing household energy flow and by tackling the issue of increase in energy tariff and attracts subsidy/financial incentives to the consumers with further reduction in tax for uptake of this technology.

3. Another sub-system in the model is subsidy/financial incentives to consumers for uptake of technology like micro-generation. This sub-system is another important policy of the government in making sure that energy security is guaranteed at all times by increasing the uptake of alternative energy source *i.e.* micro-generation and helps in reducing energy tariff. However, availability of energy subsidy may have rebound effects on energy consumption by spending the savings accrued on increased energy consumption. The energy subsidy sub-system has a number of variables and feedback loops that control the behavior of the system under study.

4. Household energy consumption behavior is another sub-system that worth discussing. Dietz et al. (2009) argue that behavior is influenced by a complex blend of demographics, values, intentions, situational characteristics and psychological factors. In this sub-system, behavioral intention to consume energy reinforces household energy consumption and invariably leads to increment in CO_2 emissions. While energy tariff as one of government policies and the cost expended on energy try to

stabilize the household behavioral intention to consume energy, increase in household income reinforces their consumption pattern.

4.1.2.2. Model Boundary

This section discusses the boundary for the model. As highlighted in section 3 previously, one of the strengths of SD is in its ability to deal with feedback structure. It is well known that every feedback structure has a closed boundary. As one of the modeling process in SD, it needs to clearly define the model boundary since it is practically impossible to include all the variables in the model. In this research, the variables to be used for the model are extracted from the relevant literature including government documents. Table 1 then shows the variables included in the model and the ones that are not considered in the present version of the model. The variables included in the model are divided into two namely: (1) endogenous – dynamics variables involved in the feedback loops of the system; and (2) exogenous – variables whose values are not directly affected by the system.

Table1. Model Boundary

Endogenous variables	**Exogenous variables**	**Excluded variables**
Climatic effects	Surface temperature	Factors influencing international fuel price like war, etc
International fuel price	Rainfall	Other factors that can cause catastrophic climatic effects
Government policy change	Snowfall	
Alternative energy sources i.e. micro-generation	Sea level	
Energy subsidy on alternative energy sources	Householders health	
Energy tax		
Energy tariff		
Energy expenses		
Fuel poverty		
Fabric insulation improvement		
Energy efficiency in dwellings		
Household income		
Household behavioral intention to consume energy		
Household energy flow		
Household energy consumption		
CO2 emissions		

4.1.2.3. Reference Modes for the Model

The next step under the system conceptualization in SD is to give a plot of the behavior of key variables in the model over time. This is referred to as reference mode or behavior chart. The reference mode depicts historical data and/or mental models in graphical form and forms the basis for comparison once the model is built. Figures 2 and 3 illustrate examples of some of the main reference modes for the model.

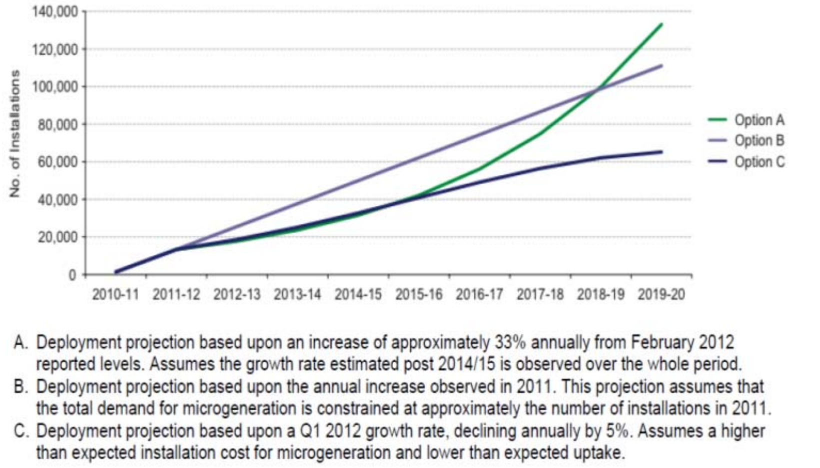

Fig. 2. Uptake of micro-generation (The Scottish Government, 2012)

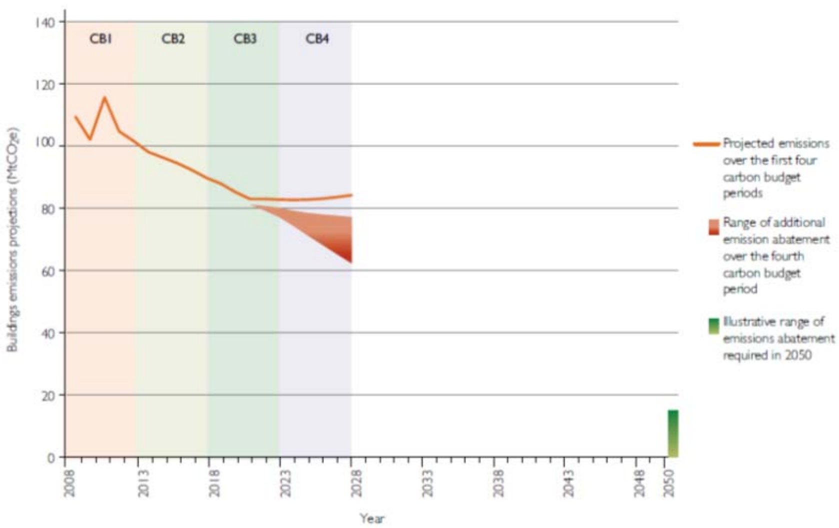

Fig. 3. Carbon emissions projections (DECC, 2012c)

4.1.2.4. The Main Causal Loop Diagram

Achieving CO_2 emissions reductions target is critical to the UK government based on the Climate Change Act of 2008. Fig. 4 illustrates the main CLD developed for the problem under investigation. The key variables and their relationships are shown in the diagram which demonstrates the use of SD in adding to the understanding of this complex system. The CLD so developed indicates that there are many feedback loops. The polarity attached to a given feedback loop is achieved by summing up the negative polarity of each of the variables within such a loop. Loops with an even number of negative relationships among the variables are regarded as positive (self-reinforcing loops), whereas, the ones with an odd number are negative (self-balancing loops). It is necessary to mention that loops with zero negative relationship are taken as being even. Also, it is worth mentioning that variables within the self-balancing loops will stabilize over time, whereas variables within self-reinforcing loops will continue to increase indefinitely.

As earlier noted that the CLD presented in Fig. 4 shows many self-reinforcing feedback loops causing instability in the system, only some of these loops will be taken for demonstration purpose only. Indicated in Fig. 4 are three self-reinforcing loops (R1 – R3). R1 is consumption loop and contains variables like [Household energy consumption – CO_2 emissions – Climatic effects – International fuel price – Household energy flow]. R2 is subsidy loop, which is provision of subsidy for uptake of alternative energy like micro-generation which increases household energy flow and therefore encourages more energy consumption by householders. This loop contains the following variables: [Energy subsidy on alternative energy sources – Household energy consumption – CO_2 emissions – Climatic effects – Government policy change]. Further, energy tariff loop (R3) is causing instability in the system and contains the following variables [Energy tariff – Energy expenses – Energy tax].

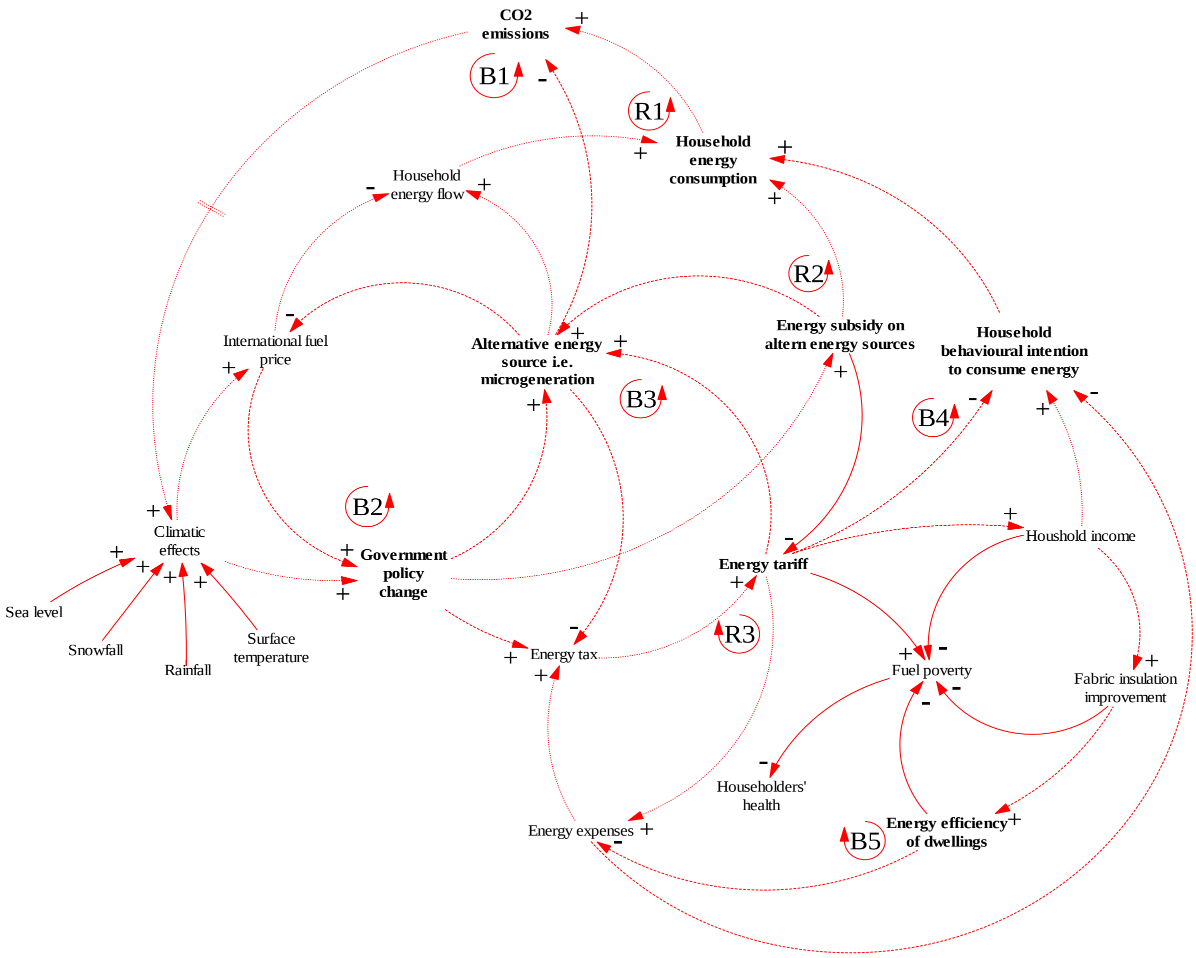

Fig. 4. Main Causal Loop Diagram

In order to counter the instability caused in the system as a result of the self-reinforcing loops, the self-balancing loops are created. Five of the self-balancing loops (B1 – B5) in the model are as indicated in Fig. 4. B1 is termed the emission loop. CO_2 emissions is been reduced based on the policy of government on provision of alternative energy that is cleaner and renewable. This loop contains [CO_2 emissions – Climatic effects – Government policy change – Alternative energy source *i.e.* micro-generation]. Also, the instability in the system is calmed down by different policies of the government (B2 - government policy loop) which contains variables like [Government policy change – Alternative energy source *i.e.* micro-generation – International fuel price]. B3 is alternative energy source loop [Alternative energy source *i.e.* micro-generation – Energy tax – Energy tariff]. Loop B4 is consumption behavior loop [Household behavioral intention to consume energy – Household energy consumption – CO_2 emissions – Climatic effects – Government policy change – Energy tax – Energy tariff]. An attempt to carry out fabric insulation improvement, which undoubtedly improves the energy efficiency of dwellings, is reflected in loop B5 (energy efficiency loop) [Energy efficiency of dwellings – Energy expenses – Energy tax – Energy tariff – Household income – Fabric insulation improvement].

Once the model is set-up, it will mean that there will be needs to pay special attention to some of the variables in the loops causing instability in the system (especially the time – dependent ones).

5. Conclusion and Further Work

This paper has demonstrated the efficacy of system dynamics tool in adding to the understanding of policies regarding household energy consumption and CO_2 emissions. Authors advocate that there are many interrelated variables in play, the analysis of which will further help in relieving the pressure being mounted by the need to significantly reduce household energy consumption and meet up with the CO_2 emissions reductions targets. The CLD developed illustrates the importance of SD as a methodology to simulate various policies regarding CO_2 emissions reductions target. Feedback loops are shown that need close monitoring in order to stabilize the system performance under consideration. The next stage of the research is to translate the CLD to SFD and relate all the variables in the model together with algebraic equations. The simulation will be run and the output of the simulation is presented in the form of graphs. Validation of the model will then be carried out accordingly. Based on these outputs, policy analysis and improvement can then be conducted and correct policy improvement is implemented.

6. Acknowledgement

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Ongoing Commissioning of a high efficiency supermarket with a ground coupled carbon dioxide refrigeration plant

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Abstract:
A significant reduction in the energy consumption and greenhouse gas emissions of supermarkets can be reached by the combination of several innovative components and the continuous optimization of their operation. A German food retail chain developed a new supermarket concept combining several innovative solutions for the refrigeration, lighting and heating/ventilation with the goal to reduce the energy consumption by about 30% compared to a standard subsidiary. A highly insulated building envelope, the use of daylight and covered refrigeration units contribute jointly to reach the goals. The key component of the concept is a carbon dioxide refrigeration plant with waste heat recovery. To reduce the efficiency losses in supercritical operation, carbon dioxide is cooled through a borehole heat exchanger using the ground as a heat sink. In the paper the design concept, the results of simulation studies and of the first monitoring year are presented and discussed.

Keywords:
Supermarket, refrigeration system, carbon dioxide, heat waste recovery, daylight.

1. Introduction

About 24 GWh/a electricity are consumed each year in Germany for the production of cooling energy by the food retail industry (Jakobs, 2006). It represents about 345,000 tons of indirect carbon dioxide emissions. Furthermore, the big majority of the about 50,000 supermarkets in Germany are running on synthetic refrigerants (HCFC, HFC) with high global warming potentials values (GWP). Accordingly to (Kauffeld, 2009), the refrigerant charge losses due to leaking refrigeration plants of the food retail industry has an amplitude of 5 up to 10%. He estimates supermarket refrigeration systems to be the “strongest emission source of fluorinated hydrocarbons in Germany”. In the meantime, significant efforts have to be achieved in the next years by the food retail industry to reduce its direct and indirect greenhouse gas emissions and contribute to the European “20-20-20” targets. The branch has to conform to always more restrictive energy building regulations, deal with a growing demand of frozen products, and cope with rising energy costs, making energy efficiency and emissions reduction one of their first strategic goal. Nevertheless, the potentials for emissions reduction and energy savings are high as most of the supermarkets are built with poorly insulated envelopes. Furthermore, a large majority of facilities do not utilize natural lighting, and are operating with refrigeration plants on synthetic refrigerants with high GWPs and without heat recovery systems.

In Germany, most of the biggest retail store chains have commissioned in the last years supermarket prototypes aiming to ambitiously reduce greenhouse gas emissions through innovative building and refrigeration concepts. Nevertheless, these projects have kept prototype characters and published scientific results and analysis from their operation are little available.

After having proceeded to a countrywide analysis of the energy structure and performance of more than 300 supermarkets, one of the major German retail companies decided to design a new supermarket, with the main objective to radically reduce its primary energy consumption through the implementation and evaluation of new technologies for refrigeration, building envelope, heating and ventilation and lighting. The project is funded by the EnOB program (Energie Optimiertes Bauen: energy optimized buildings) led by the German Federal Ministry of Economics and Industry, which aims to test and demonstrate energy efficient technologies in different building types. The program mandates a reduction of the primary energy needs for heating, cooling, ventilation and air conditioning (HVAC) and lighting, of at least 50 % compared to the mandatory targets fixed by the Energy Saving Regulation and calculated accordingly to the norm DIN 18599 (EnOB, 2006) (EnEV, 2009). The current project described in this article widens the typology of the EnOB program to the food retail branch and aims to show the positive effect of new technologies and to disseminate the monitoring results on a large scale. (EnOB, 2011)

The primary energy consumption of a standard supermarket of the food retail chain for refrigeration, lighting and hvac´s amounts to about 500 kWh/m^2.a. The share for heating with fossil fuels is about 11 %. The electrical energy consumption is dominated by refrigeration and lighting with respective shares of 54 % and 30 %. One of the main project objectives was to obtain a 29 % reduction of the primary energy needs of the new supermarket for refrigeration, lighting and hvac´s with respect to a standard supermarket. The resulting specific primary energy consumptions of the different significant energy users are listed in Table 1. A primary energy factor of 2,6 is considered for electricity and of 1,1 for natural gas.

Table 1 Primary energy consumption targets for the new supermarket

	Specific primary energy consumption [kWh/m^2.a]		
Building system	*Standard supermarket*	*New supermarket*	*energy reduction objective [%]*
Heating (gas)	*56*	*-*	*- 100%*
Refrigeration	*276*	*256*	*-7 %*
Lighting	*118*	*83*	*- 29 %*
Air conditioning	*34*		*- 100 %*
Ventilating	*18*	*10 /*	*-46 %*
Heat pump	*-*	*8*	
Total heating/cooling/ ventilating/lighting	*226*	*101 /*	*- 55 %*
Total	*501*	*357 /*	*- 29 %*

The use of a dynamic simulation model showed that these objectives could be reached by combining several innovative building envelope, refrigeration, lighting and HVAC technologies. Another objective was the use of a refrigeration plant prototype running on climate friendly CO_2 as refrigerant and coupled with a waste heat recovery system and a borehole heat exchanger. The borehole heat exchanger can be used as additional heat sink for refrigerant sub-cooling in summer operation and heat source for a heat pump compressor which supplies additional heat to the supermarket when the heat waste recovery is poor at low outdoor air temperatures. This system made the use of a gas boiler superfluous.

The store chain engaged to adopt on large scale the tested technologies which shall prove their value under the perspective of both environmental and economic criteria. The replication potential for the successful technologies is high as the store chains builds or renovates yearly over 100 stores in Germany. Hence the systematic validation of the different parts of the new concept is of major importance for the decision makers.

In this paper, we first describe the new supermarket design and deliver the results of dynamic simulation studies which supported the determination of energy reduction objectives for the significant energy users. In the second part, we show the results of the analysis and optimizations conducted during the first monitoring year on the refrigeration, HVAC, and lighting systems as well as a comfort analysis.

2. Supermarket concept description and objectives

2.1. Building envelope

The supermarket envelope was designed and built in accordance to the German passive house standard. The U-values of the different components are listed in the Table 2. The airtightness of the building measured through a blower door test reached an air change rate of 0,47 h^{-1}, below the passive house standard threshold value of 0,60 h^{-1}. The windows and skylights are fitted with triple glass window panes.

Table 2 Physical data of the envelope components

Envelope Component	*U-Value [W/m^2.K]*
Roof	*0,14*
Foundation concrete slab	*0,29*
External walls	*0,18*
Skylights g = 0,29	*1,26*
Windows and glazed doors g = 0,50	*0,70*

2.2. Heating and ventilation concept

In a standard subsidiary, the heating and cooling are covered by an air handling unit with an air flow rate of 12,000 m^3/h. Heat is supplied by the waste heat recovery system of the refrigeration plant and a gas boiler. A split-system supplies a direct evaporator for the air cooling. In the new supermarket, the heat is provided from the desuperheating of CO_2 at temperature levels and energy amounts which allow avoiding the use of an additional gas boiler. As depicted in Figure 1, analysis from dynamic simulation showed that heating demand occurs all year long due to the influence of the heat sinks in the supermarket (multi-desk cabinets and remote island freezers). Thus, the split-system could also be dropped out. The heating of the sales area is assured by an activated concrete slab supplied by the waste heat recovery exchanger of the refrigeration plant and designed with 26°/22°C water temperatures. This new system allows downsizing the air handling unit to the minimal hygienic rate of fresh air to 4,600 m^3/h. Thus, driving energy can be saved. A higher thermal comfort for personel and clients can also be targeted with this radiant heating system. The air handling unit is a 100% fresh air single duct plant with a rotational heat recovery system ensuring a nominal air change rate of about 0,5 h^{-1}. The air flow of the air handling unit is controlled with air quality sensors which limit the maximum carbon dioxide concentration in the supermarket at 1500 ppm. Nearby the suppression of fossil fuels, the dynamic simulation model showed that a reduction of 47% of the power consumption for the supermarket ventilation can be targeted.

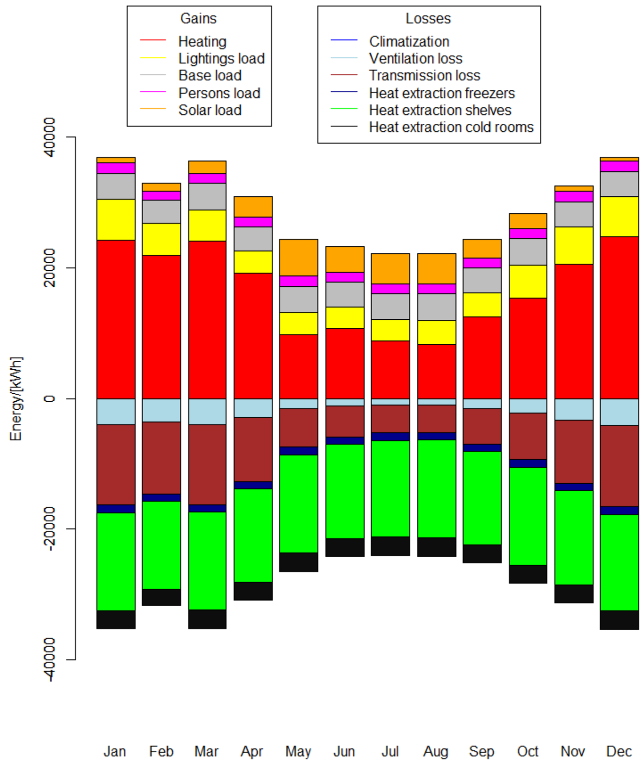

Figure 1 monthly heat and refrigeration demand and balance in the supermarket (simulation results)

2.3. Refrigeration system

To reduce the direct greenhouse gas emissions from the refrigeration plant through unavoidable leakages, the owner of the supermarket chain choose the climate friendly refrigerant carbon dioxide. Carbon dioxide - CO_2 or R744 - is one of the oldest refrigerants and was widely used in industrial and marine air conditioning from the end of 19^{th} century until the middle of the 20^{th} century. The phasing out of ozone depleting CFCs (chlorofluorocarbons) and HCFCs (hydrochlorofluorocarbons) after the Montreal Protocol in 1987 and the global warming potential of widespread HFC (hydrofluorocarbons) gases like R134a and R404a led to a revival of environmental friendly gases like carbon dioxide, ammonia or hydrocarbons. The advantages of R744 towards synthetic refrigerants are its high environmental compatibility with an Ozone Depletion Potential (ODP) of zero and a GWP of 1, its high chemical stability and its excellent thermodynamic properties. The high volumetric heat capacity of R744 allows the choice of smaller components and distribution lines. Furthermore, R744 chillers can reach higher energy efficiency at low condensing temperature than plants running on synthetic refrigerant like R404A, allowing a large scale application in countries with moderate to cold climates. Compared to natural refrigerants like NH_3 or butane, R744 has the advantage of being non-toxic and non-flammable. Drawbacks of R744 are its high critical pressure (73.77 bar) and its low critical temperature (31.1 °C) which require the use of cost intensive high pressure components.

Figure 2 depicts the schematics of the refrigeration plant. The different points of the refrigeration circuit are also reported on the log p,h diagram on Figure **3**. In this article, we focus on the high pressure side of the refrigeration plant. The thermodynamic process on the low and medium pressure sides are not further detailed here. The first role of the refrigeration system is to ensure the fresh-keeping at +4°C and the freezing of food at –25°C. The plant is a two-stage system with a booster connection between the two low temperature stage compressors (LT Comp.- points 15-16) and three medium temperature stage compressors (MT Comp. – points 7-8). It serves all the cooling points in the supermarket like multi-desk cabinets, island freezers and cold rooms as well as an automatic bread machine over a distributed piping system. The installed refrigeration capacity for MT-cooling is 50,3 kW and 16,7 kW for LT-cooling. The island freezers are equipped with double glazing with low emission layer to reduce the transmission losses to the indoor environment. For the same reasons, a thermally insulated energy saving blind covers the multi-desk cabinets when the supermarket is closed. All the multi-desk cabinets and island freezers are fitted with LED lamps and high efficiency fans with internally commutated motors.

After the second compression stage, the high-pressure R744 vapor flows first through a heat recovery heat exchanger (points 8-9) where it transfers its heat to a hot water loop connected to the air handling unit and the activated concrete slab. Then, the remaining heat is rejected to the outdoor air over a gas cooler (9-10). The third heat exchanger (10-1) is connected to a borehole heat exchanger with six vertical U-tubes with a length of 100 m each. The role of this heat exchanger is to further cool down the R744 to enhance the energy efficiency of the refrigeration system in the sub- and the transcritical operation. At low outside air temperature, the heat recovered from the R744 vapor cannot compensate the heat demand of the supermarket, thus an additional compressor, working as a heat pump and extracting heat from the borehole heat exchanger has been employed. In the case of a subcritical operation, the high-side pressure is determined by the condensing temperature until an outdoor air temperature of about 20°C. When the outdoor air temperature exceeds this mark, the transcritical operation cannot be avoided due to the low critical temperature of R744. In the same time, there is only a low heat demand from the building so that most of the heat has to be rejected to the outdoor environment. When the system operates in transcritical region, there is always a maximal COP for each outdoor air temperature (Cecchinato, 2009). At increasing discharge pressure, the maximal COP is reached when the increase of the cooling capacities cannot compensate the additional compressing work. Unlike concepts aiming to reach an optimal COP by controlling the discharge pressure on the high pressure side, the high pressure is controlled here at a constant value of 75 bars which allows reaching the highest COP by using the subcooling effect of the borehole heat exchanger. Figure **3** depicts the transcritical refrigeration cycle as it occurs in summer and shows the cooling effect of the borehole heat exchanger after the gas cooler.

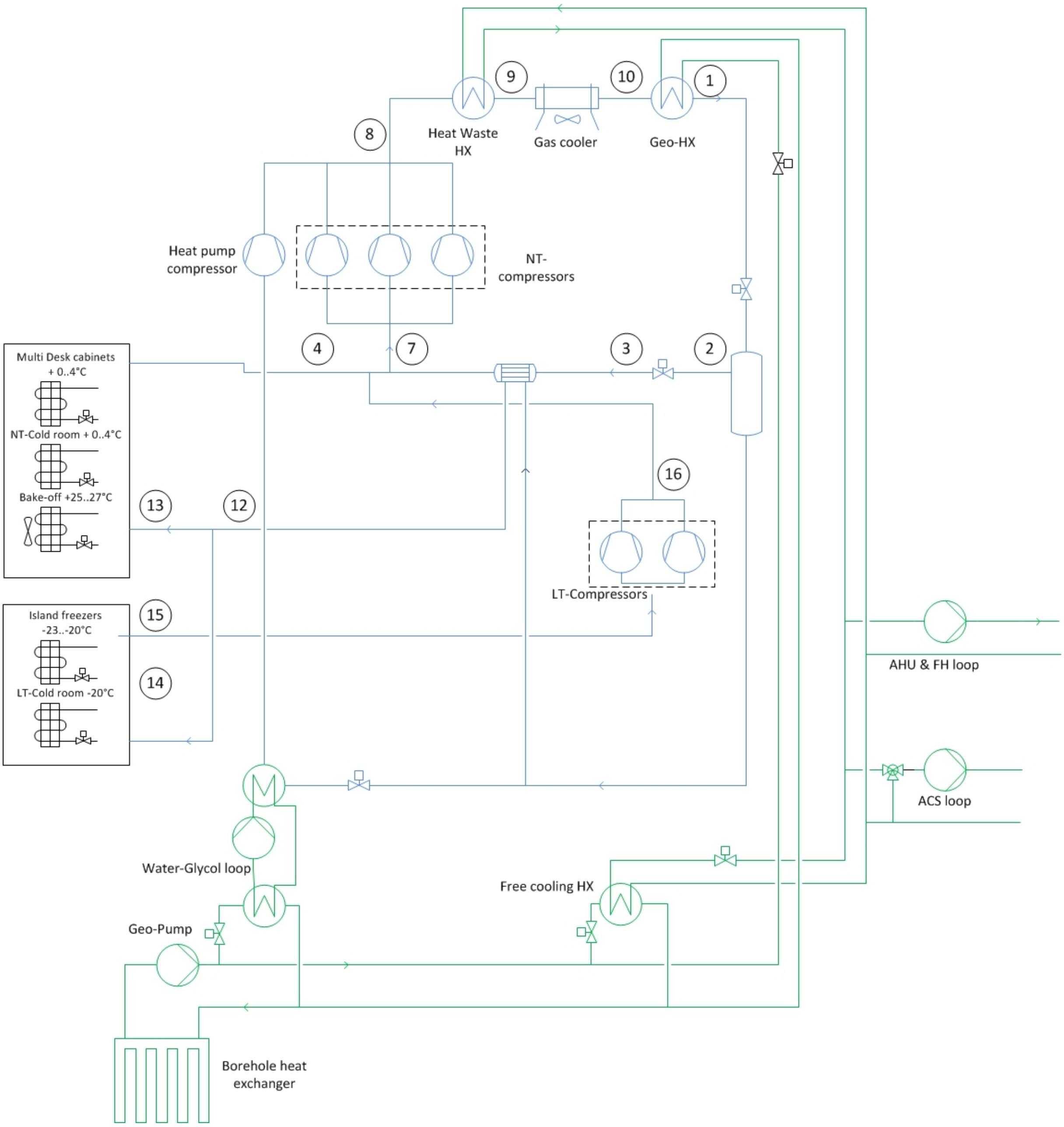

Figure 2 Schematic of the R744 refrigeration plant with borehole heat exchanger

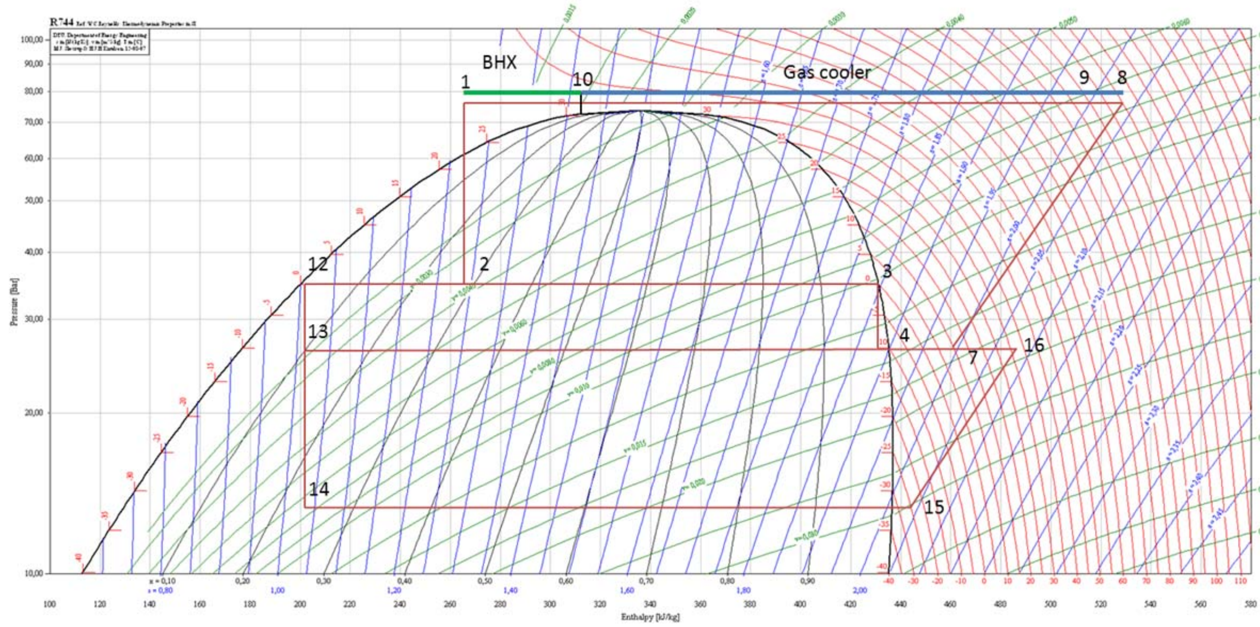

Figure 3 R744 pressure – enthalpy diagram with transcritical refrigeration cycle and gas cooler and borehole heat exchanger shares for the refrigerant desuperheating and cooling

Energy consumption objectives based on manufacturer's data were calculated with the simulation model. The yearly energy consumption of the refrigeration plant was calculated with a COP of 3,7 for the low pressure compressors and of 2,7 for the medium pressure compressors. Thus, a specific primary energy consumption of 256 kWh/m^2.a could be targeted for the refrigeration system, representing a reduction of about 7% of the refrigeration energy needs of a standard supermarket.

To validate the concept, sensors and meters were installed. The refrigerant pressure and temperatures on the high pressure side and after the evaporator groups are measured every minute and enthalpies are automatically calculated over an interface with thermodynamic properties tables based on RefProp. Power meters have been installed for each compressor group and for each major electrical component like the gas cooler or pumps. Heat and cold meters have been installed in each water circuit. Power calculation in the refrigerant circuit could not be achieved until now because of measurement issues with the installed coriolis mass flow meters. Thus, only enthalpy differences between the in- and outlet of each heat source and heat sink could be calculated.

2.4. *Lighting concept*

Natural light has complex physical and psychological effects on the human body; it supports well-being, affects positively the productivity and can significantly contribute to energy savings. Using day lighting also has aesthetic benefits that encourage customers to enter stores and has positive effects on sales (Edwards, 2002). The preliminary study on the energy use in over 300 subsidiaries of the food retail chain showed that lighting energy constitutes about 29 % of the total energy use of a standard supermarket with a median primary energy demand of 118 kWh/m^2.a, and is therefore an important area for energy conservation. A new daylight concept using 28 triple glazing skylights with integrated reflection gratings was developed, simulated and implemented. A restrictive constraint by using daylight is to preserve the food products quality from damaging direct sunlight. To overcome this issue and allow harvesting the maximal diffuse light quantity, the number, orientation and disposition of the skylights were optimized in a daylight study supported by a dynamic simulation with the software packages Radiance/Daysim/TRNSYS. The results of the simulation showed that a reduction of about 30 % of the energy use could be reached in this supermarket in comparison with a standard supermarket without use of daylight. The basic lighting of the sales room and the warehouse is achieved with T5 fluorescent lamps. Directional spotlights with metal-halide lamps ensure the effect lighting for cosmetics, food and promotional items. The artificial basic lighting is dimmable and controlled by mean of light meters to ensure a minimal illuminance level of 700 lux at a height of 1,30 meter in the sales area. Through this, the output of the electric lighting system can be adjusted in response to changing amounts of natural light. All the lights are turned off from supermarket closure at 8 pm to opening at 7 am and on Sundays. Outside the opening hours, the basic lighting is dimmed at 30 % of the nominal power for preparation tasks.

3. MONITORING

The aim of the monitoring phase was to continuously optimize the energy efficiency of the different systems, with a special focus on the refrigeration plant and the lightings, while collecting additional knowledge on the energy operation of the supermarket and identifying areas with further optimization potentials.

3.1. *Refrigeration plant*

The refrigeration plant of the new supermarket is the first transcritical R744 chiller which was build and commissioned by the manufacturer and has therefore a prototype character. Hence, after commissioning, the first goal was to produce cold and heat for the normal and safe operation of the supermarket.

The following optimizations were implemented during the first monitoring year to improve the energy efficiency of the plant:

- Just after the commissioning, the high pressure was controlled in subcritical operation at a constant value of 65 bars. The implementation of a condensing temperature dependent high-side pressure control was first achieved during summer 2011, leading to a reduction of the compressors work.
- During the winters 2010/2011 and 2011/2012, the heating cycle was supported by switching from the subcritical operation to the transcritical operation to benefit from higher temperature levels. This control strategy was changed at the beginning of 2012

by supporting the heating with the heat pump compressor exclusively in subcritical operation.

- The evaporation temperatures of the cooling points were first fixed values. In summer 2011, a control software was implemented which continuously optimizes the set values and the compressors rotation speeds.

In 2011, the specific primary energy consumption of the refrigeration plant reached 298 kWh/m^2.a and laid 14 % over the objective. These results are nevertheless encouraging considering the prototype character of the plant and the fact that optimizations were implemented step by step during the first year.

Figure **4** depicts the shares of the different components on the high pressure side in cooling the R744. Over the whole year 2011, about 25% of the R744 heat is decoupled by the heat recovery system, amounting to 47,8 MWh. In winter, this share rises to over 50 %. Without heat demand in summer, the gas cooler contributes on average 90% of the desuperheating and cooling. The remaining 10 % are ensured by the borehole heat exchanger. The mean value of the power consumption of the borehole heat exchanger pump amounted to 4% of the power consumption of the compressors power consumption, so that an energy efficiency gain of about 6% could be reached by the use of the borehole heat exchanger.

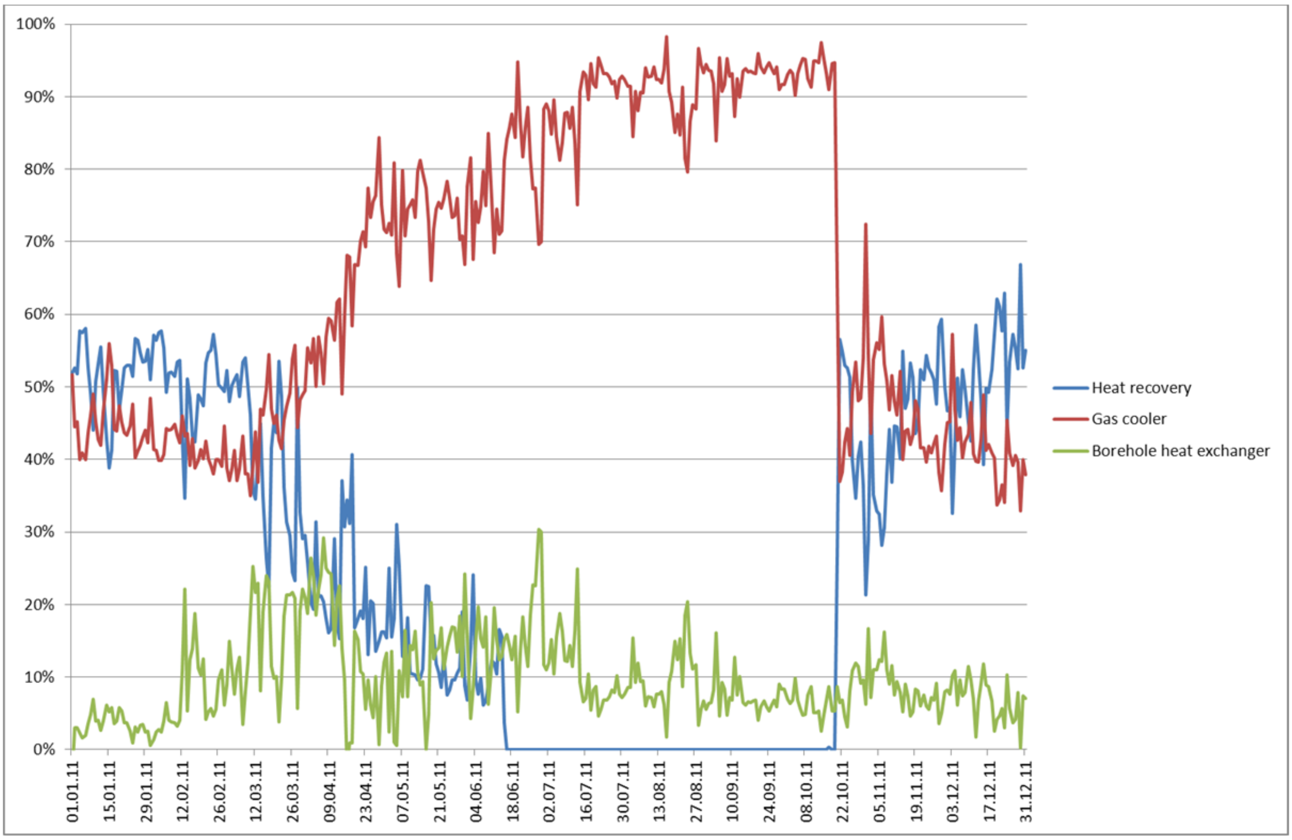

Figure 4 Shares of R744 enthalpy differences of the heat recovery system, the gas cooler and the borehole heat exchanger during year 2011

3.2. Heating / cooling

The new heating and ventilation concept has been evaluated in terms of energy efficiency and comfort.

Thermal comfort analyses in a supermarket are primarily used to assess the working conditions of the supermarket staff. The methods described in the norms EN ISO 7730 and EN 1525 were used. The boundaries and the corresponding PMV and PPD indexes of each category are compiled in Table **3**.

Table 3 Category boundaries for winter and summer period and PPD/PMV indexes

Building Type	Category	Minimum value for heating periode in °C for / Maximum value for summer period in °C	PPD* %	PMV**
Department store (ALDI), 1,6 met	I	20.0 / 24.0	< 6	-0.2 < PMV
	II	19.0 / 25.0	< 10	-0.5 < PMV
	III	18.0 / 26.0	< 15	-0.7 < PMV

The comfort categories I, II and III respectively represent a high, a moderate and a low level of comfort expectations. Figure 5 depicts the dependency between the hourly average of the indoor air temperature and the daily moving average of the outdoor air temperature in 2011. The three comfort categories are represented by the intervals between the horizontal lines for winter and summer conditions. In winter, the indoor air temperatures fall below the category I only in 16% of the time during the first year and category III was not maintained in only 1 % of the time. Category I was exceeded 17 % of the time and only 1 % of the measurements did not uphold to category III.

In summer, the room temperatures exceeded the category I threshold during only 2% of the time. Temperatures fall in category II about 40 % of the time in summer. 11 % were in category III and 2 % outside category III.

This analysis shows that a good thermal comfort could be obtained in winter as well as in summer already during the first operation year. Some enhancements of the comfort conditions are possible by low outside air temperature through additional heating by an enhanced heat pump operation. In summer, no heating occurred unlike the results of the simulation. Nevertheless, a slight heating could be foreseen to enhance the comfort during this season.

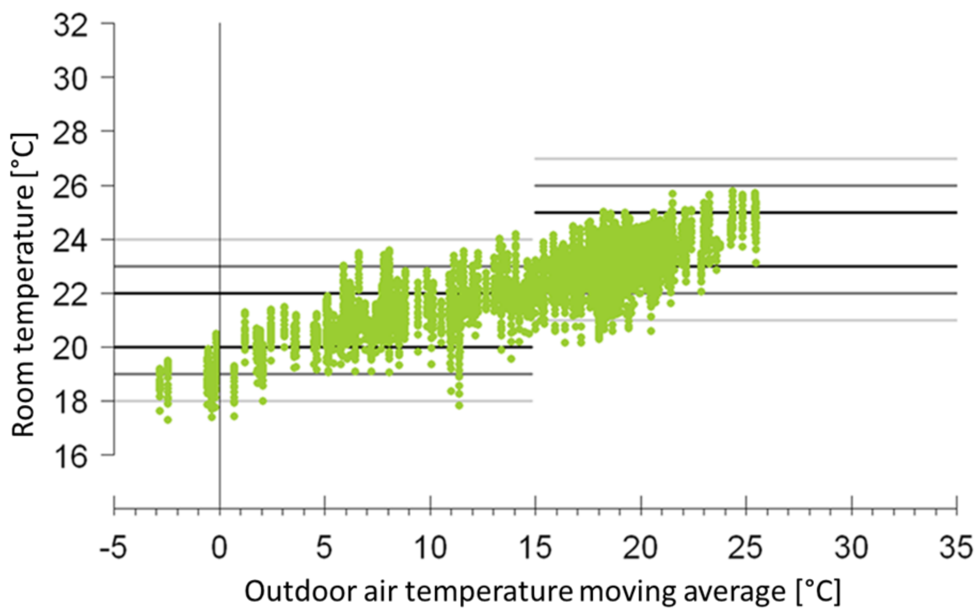

Figure 5 Relationship between hourly average of the room temperature and moving daily average of the outdoor air temperature

3.3. Ventilation

The role of the air handling unit is to control the indoor carbon dioxide level at a maximal value of 1500 ppm in order to ensure a good air quality in the supermarket. The specific primary energy consumption of air handling unit amounted to only 1 % of the energy consumption of the supermarket in the first year. With 7,0 kWh/m^2, it corresponds to a reduction of about 60 % of the energy consumption needed to ventilate a standard supermarket. The results lie also about 27 % under the objective of 9,8 kWh/m2.a. This concept could allow controlling the air quality at a very high level without significant energy efficiency losses.

3.4. Lighting

In 2011, the inner lightings consumed 67,11 MWh electrical power. It corresponds to a specific primary energy consumption of 101 kWh/m^2.a. This result lays about 21 % above the targeted value of 83 kWh/m^2.a. Several reasons listed below were identified that explain the deviation from the objective.

- The higher limit for the power input was set to 16,0 kW whereas the set value of 700 Lux for the illuminance could be reached with only 85 % of the nominal installed power. Therefore, this threshold has been reduced to 14,0 kW. The same measure was implemented for the minimal power input through a reduction of the lower threshold from 5,5 kW to 3,0 kW.
- The dimming of the basic lighting to 30 % of the maximal value in the morning before public opening was not strictly respected by the shop employees, inducing an increase up to 10 % of the daily energy consumption. The food retail chain

management raised the employee awareness on this problem resulting in a better compliance to the guidelines.

- The schedules of the effect lightings were not implemented correctly as these were switched on from 7 am instead of 8 am.
- The switching interval for the artificial light control of the warehouse was set too high, which did not allow an energy efficient dimming.

The optimization measures which were implemented during the first year of the ongoing commissioning campaign allowed a reduction of the energy consumption of the lighting over the months visible in Figure 6. Based on data of the first half of 2012, an energy consumption of 88 kWh/m^2.a can be forecast for the lightings. This calculated value is of course dependent on the future sun radiation supply but converges strongly towards the targeted value of 83 kWh/m^2.a.

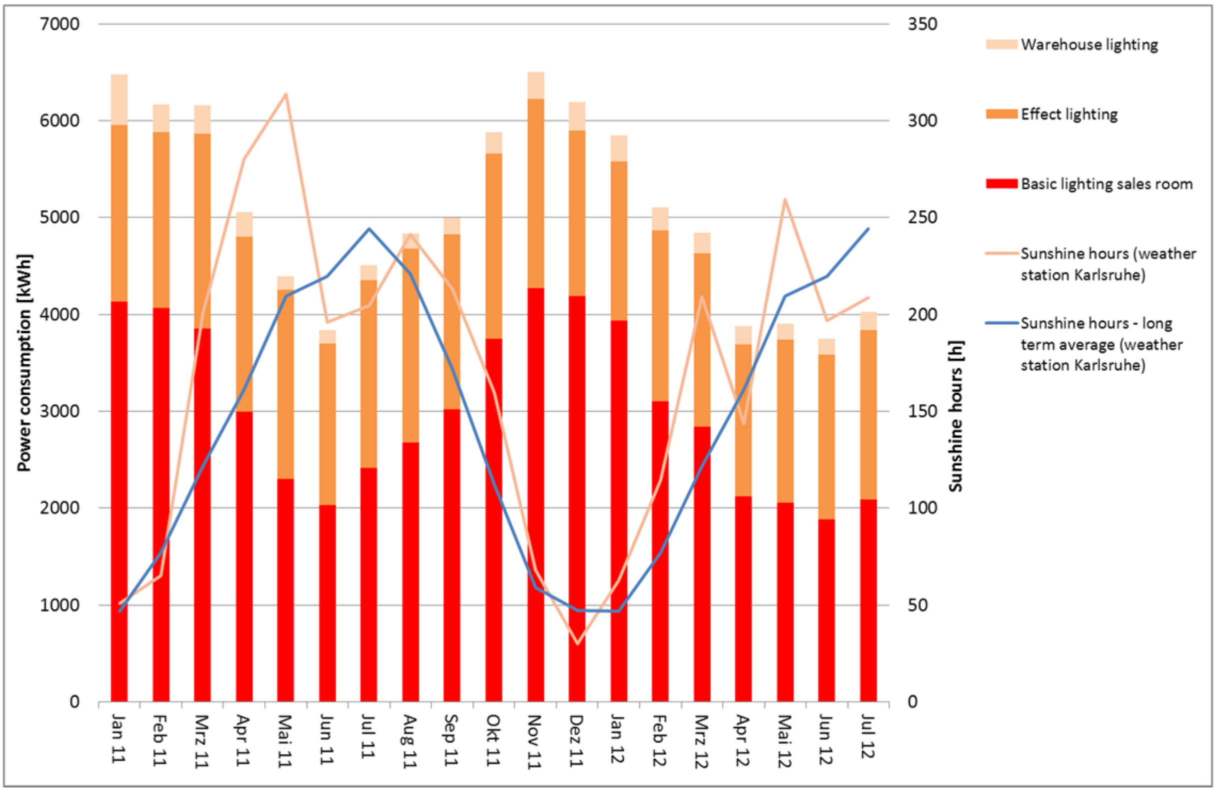

Figure 6 Electrical power consumption of lightings from Jan. 2011 to July. 2012

4. Conclusion

As depicted in Figure **7**, the specific primary energy consumption of the supermarket reached about 408 kWh/m^2.a after the first operation year. It represents a reduction of 20 % of the energy consumption of a standard supermarket of the food retail chain. Gains of about 13 % in the energy efficiency of the different components still have to be obtained in the next year to reach the goals.

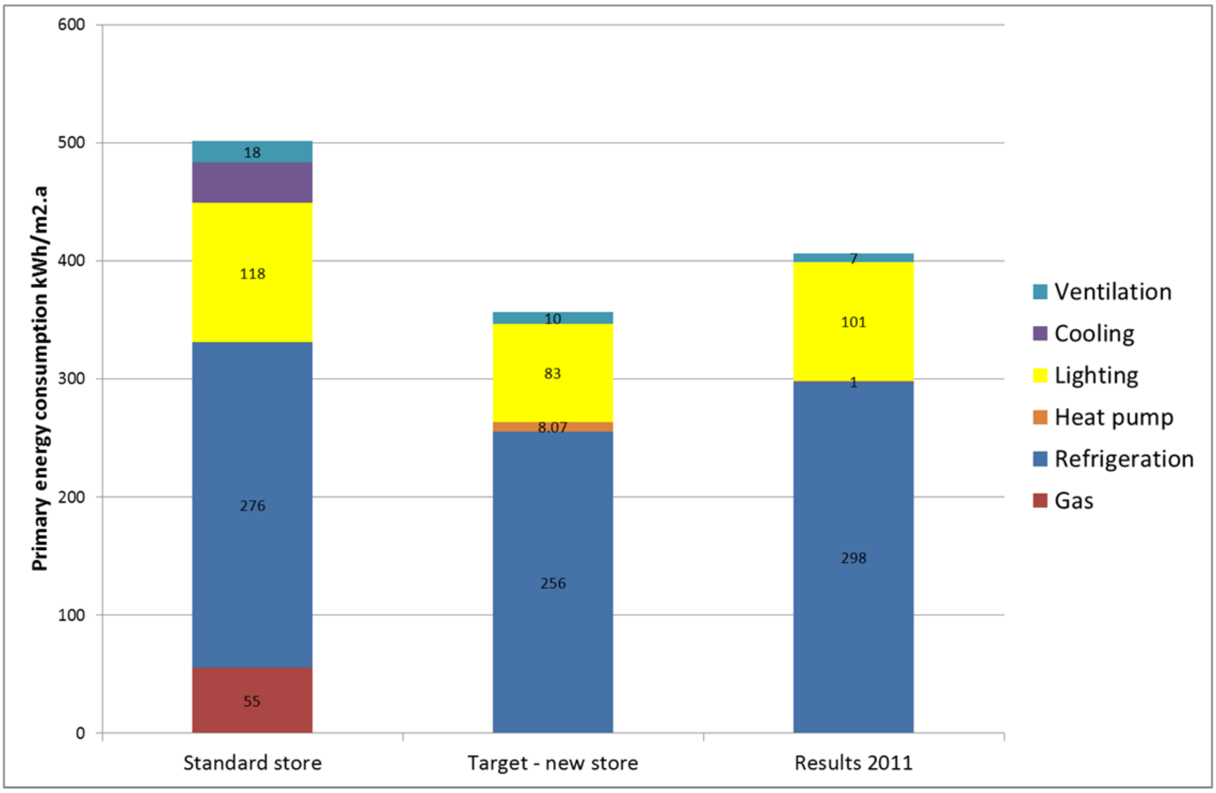

Figure 7 Comparison of the energy consumption targets with measurements after one year

The first monitoring period of the new supermarket could allow validating some basic components of the new concept in term of energy efficiency and comfort like the activated concrete slab, the air handling unit and the transcritical carbon dioxide chiller. In particularly, the new refrigeration system on R744 could perform almost as well as a standard chiller using synthetic refrigerants thanks partly to the cooling effect of the borehole heat exchanger. Nevertheless, the operation of the borehole heat exchanger still need to be optimized and analyzed to harvest the highest potential from this heat sink and show its economic viability as investment costs are high for such a technology. Lessons learned from the first monitoring year have already been implemented in the development of a new chiller generation which will be commissioned in the course of 2012 in a new subsidiary of the food retail chain. Regarding the use of daylight, the high costs of the new roof and the competition with photovoltaic could hamper a large scale replication despite the high interest of the daylight concept in terms of visual comfort and energy savings. Here, new concepts and products have to be developed to allow a smooth and economic architectural integration.

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BUILDING INFORMATION MODELLING (BIM), UTILISED DURING THE DESIGN AND CONSTRUCTION PHASE OF A PROJECT HAS THE POTENTIAL TO CREATE A VALUABLE ASSET IN ITS OWN RIGHT ('BIMASSET') AT HANDOVER THAT IN TURN ENHANCES THE VALUE OF THE DEVELOPMENT

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KEYWORDS: BIM, Asset, Data, Value, Evidence.

ABSTRACT:

BIM currently appears to be seen primarily as a vehicle to deliver efficiencies within the design and construction phases of built assets lifespan.

In this paper we postulate that the amalgamation of the data and its capture in the BIM technologies, models and associated links and references has the potential to create an effective asset in its own right. The 'BIMAsset', like any other asset, will require ongoing observation and maintenance throughout the physical assets life to extract maximum value from it. A substantial part of this value is likely to be the enhanced value of the development because of the accessibility, accuracy and currency of the data relating to the project. This will be of probable benefit to all owners and maintainers of constructed assets in their use, sale and even future demolition.

1.0 INTRODUCTION

The adoption of BIM in the construction industry has revolutionised the current and future roles of professionals by bring about a more productive and collaborative workflow in the project delivery process.

BIM as a term commonly refers to designing, constructing and managing buildings but its major strength lies in its ability to maintain a digital database, which can be used together with other software in order to run simulations and deliver information to professionals in the industry (Sah and Cory, 2008). According to Eastman *et al.* (2011), BIM is a modelling technology, and associated set of processes to produce, communicate, and analyze building models. BIM can accurately capture the entire geometry and characteristics of a building in a single building model. BIM is generally seen as the technologies used to deliver projects efficiently, but as building professionals we need to look beyond that point. There is need for the industry to cast a shining light on the deliverables of the BIM process. That is to recognise the value of 'BIMAsset', 'BIM Model' and the 'Building Asset'. This paper will focus mainly on the 'BIMAsset'.

One of the presumed benefits of the 'BIMAsset' is that it will enable vendors to reinforce to investors the security of their investment, and that those projects which demonstrate these attributes will either attract a premium or reduced sale costs. This by reducing the need for repeat surveys, due diligence and compliance exercises based on perhaps scanty demonstrable evidence and substantiated detail as experienced in the past, by having up to date accurate data.

From our participation on projects, in the capacity of Client/Owner Developer through Design and Construction through to divestment and the inclusion of retained assets within our projects. We have established the notion that the 'BIMAsset' might have a life which will progress through the Design and Construction into the Operation and Maintenance phases through changes of ownership and refurbishment and final disposal.

One of the perceived challenges is the potential degradation of the data, through the life of the project and constructed facility. For example if the BIM dataset is frozen as the building enters its operation phase then the accuracy and currency of the data will degrade at the rate the assets are replaced and renewed This can be illustrated graphically and the confidence in the data set will rapidly diminish to a point where the 'BIM investment' is lost. This possible risk can be mitigated by ensuring the currency of the BIM databases are retained by recording the evolution the constructed facility caused by changes and updates. This is likely to be achieved by links through the Computer Aided Facilities Management (CAFM) system which could retain an historical record of events as well as the detailed changes similar to the way the mainframe has supported the IT industry.

This purpose of this paper is to propose the hypothesis of the existence of the 'BIMAsset', explore its composition, value, compromises, and limitations.

1.1 HYPOTHESIS

H_1: In this paper, we postulate that the amalgamation of the data and its capture in the BIM technologies, models and associated links and references (models will include design models which may be combined or linked and datasets which may consist of databases which are addressable in either direction) has the potential to create an effective asset in its own right called the 'BIMAsset'.

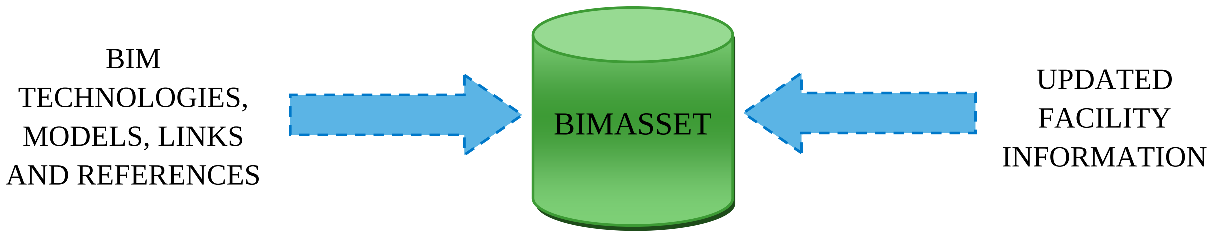

Figure 1: H_1

H_2: Also, we postulate that the deterioration in the confidence of the 'BIMAsset' data is directly proportional to the rate at which assets are replaced if the replacements are not captured within the BIM environment over the entire lifecycle of a facility.

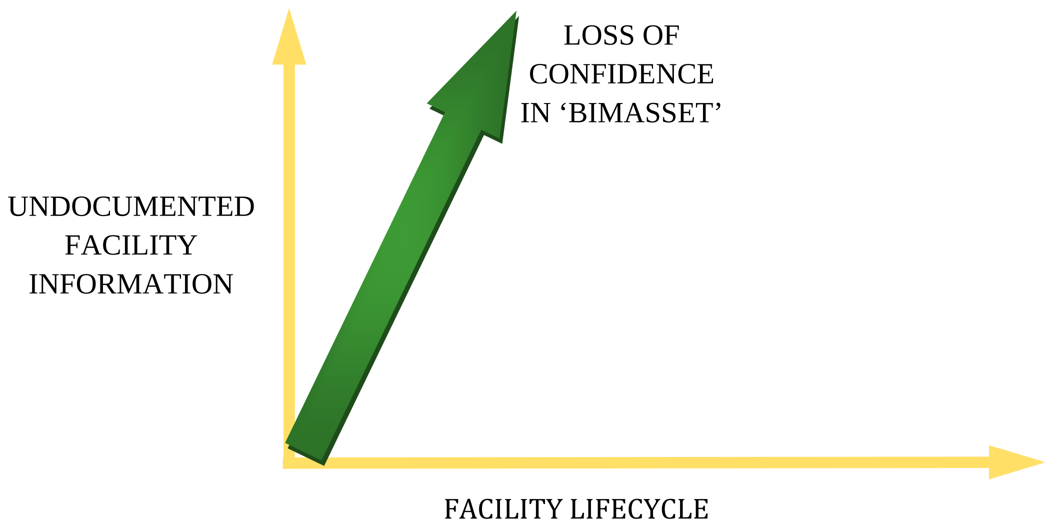

Figure 2: H_2

1.2 ASSUMPTIONS

The assumption made in this paper is as follows:

i. All elements replaced over the entire lifecycle are not of equal impact/relevance to the performance of the facility.

1.3 METHODOLOGY

The aim of this paper is to identify the potential value of the 'BIMAsset', its benefits, composition and limitation. This study achieves the aim by way of qualitative research methods. This was done by careful research of previous project records, documented professional experiences and other literary sources.

The study starts by proposing a hypothesis that the 'BIMAsset' can be an asset in its own right. To establish this proposition, we recognised the 'BIMAsset' as an informational database of the 'Building Asset' and we compared it to similar systems in other industries. For the 'BIMAsset' to be an asset in its own right, it must have a significant value. Benefits such as reduction in the cost of surveys, confidence in the dataset were investigated.

In order to establish H_2, clients were investigated to determine the rate at which undocumented replacements affect confidence levels. This is because, as an asset, confidence is vital and without proper management and frequent updating, the 'BIMAsset' dataset will be worthless. Hence, not worth the investment. Interviews of clients in this study have indicated that:

- This relationship is not directly proportional and is dependent upon the build asset component type and the level of deviation from a very high level of demonstrable accuracy before confidence falls away; the views expressed are that only a small deviation from high accuracy levels leads to a significant fall in confidence.

- That all assets are not of equal value and that the significance of the component wanes and waxes dependent upon the point in the built assets lifecycle

The hypotheses were validated through project records, literature sources and declarations from professional in the industry in terms of potential savings…

2.0 BIM AND 'BIMASSET'

BIM

BIM is an emerging procedural, technological, strategy approach in addressing the inefficiencies of the AEC industry (Succar, 2005; Eastman *et al.*, 2011). BIM encompasses a series of interrelating techniques and technologies which generates a methodology for managing project design and data in a digital format throughout the lifecycle of a facility (Succar *et al.*, 2007). BIM is not a replacement for previous design technologies like CAD, but a succession from such technologies. BIM enables construction professionals to make informative cost-time-benefit assessment on the entire project lifecycle by working collaboratively on a model (Thomson and Miner, 2007).

BIMASSET

In this paper we define the 'BIMAsset' as the combination of BIM technologies together with the updated facility information, models, associated links and references in a an interoperable structure to be handed over to clients at the point of practical completion or at the point of sale. The 'Building Model' consists of objects contained in a facility in a digital database (Eastman *et al.*, 2011). On the other hand, we define the 'Building Asset' as the psychical tangible structure constructed and handed over to clients by constructors so as to fulfil their contractual responsibilities.

2.1 WHY DO WE NEED TO RECOGNISE THE 'BIMASSET'?

The overall concept BIM is having a knowledge based repository which provides a basis for reliable decision making throughout the entire lifecycle of a facility (Zhang *et al.*, 2009). The major property of BIM is its ability to hold the entire database of a facility in a single entity. This paper mainly highlights on one deliverable of the BIM process, the 'BIMAsset', which if fully utilised will have the potential to answer questions like:

i. What are the lifecycle costs of certain elements of the system?
ii. Which elements have shorter lifecycles?
iii. What is the economic performance of the facility at the end of its lifecycle?
iv. Are all the statutory compliances achieved?

From interviewing participants within the construction industry from the Building surveying profession the following constraints have been identified and that the value of BIM Data is dependent upon:

- Confidence in the accuracy of the records that they truly represent the 'As Built' asset.
- The extent that they represent a comprehensive set of data of the built asset.
- That the design quality has been delivered by the construction activities.
- That the records have captured the operational changes to the assets to date.

Therefore, should the above circumstances exist, then there a potential transaction cost benefit for the following events:

- Sale / purchase of assets though reduction of survey scopes to confidence checking levels only.
- Technical reports relating to scope changes to assets e.g. change of use, extension omissions.
- Routine technical reports our analyses of asset performance are reduced to 'data mining' activities supplemented by sample confidence checks.
- Asset value enhancements.

Assuming the above constraints upon the data have been met significantly, higher confidence levels lead to:

- Reduced transaction time.
- Reduced input from specialist technical and legal advisors.
- Reduced fee burden upon transactions.

2.2 BENEFITS OF THE 'BIMASSET'

The benefits of a reliable 'BIMAsset' include the following:

i. Reduces survey costs
ii. Better decision making
iii. Better confidence level in assets
iv. Accurate forecasting
v. Low maintenance cost
vi. Ease of tendering
vii. Enhancing compliance with statuary obligations

- **Reduces Cost:** The 'BIMAsset' if properly managed, it will reduce the money spent on the scale of repeated surveys for developments and alterations over the lifecycle of a facility. According to clients typical surveys on a healthcare facility cost in the range of an average of £0.80 to £1.50 per m2 is spent by clients on surveys for facilities. With proper management of the 'BIMAsset' these incurred costs can be minimised by reducing surveys to sample area checking to demonstrate confidence

- **Better Decisions:** In a way, BIM provides an avenue for asset managers to engage in the decision process that will affect the design construction and use of the facility at a much earlier stage (Azhar *et al.*, 2008). This enhances the team's ability to make more informed decisions regarding the facility. The information contained in the document should provide the basis for better projections in terms of planning, maintenance, service life of the facility and reinvestment decisions.

- **Better Confidence in Assets:** The possession of a reliable 'BIMAsset' will provide more confidence in the overall investment because the client can assess the economic performance of the facility at any particular time in its lifecycle.

- **Accurate Forecasting:** Due to the amount of information accessible to managers, forecasting methods can be done more accurately and will eliminate further survey costs.

- **Low Maintenance Cost:** If the FM provider updates the BIM model automatically based upon their activities. There is will be no premium charged for maintenance. This symbiotic relationship will create a win-win situation. The client will have an updated 'BIMAsset' while the FM provider will see it as an opportunity to rake in savings through better asset identification and information retrieval. If BIM is implemented and used properly, an average ROI of 5-1 can be achieved on a single project (Munir, 2012). Therefore, ROI of the 'BIMAsset' will cover the cost for the manager required for the maintenance.

- **Ease of Tendering:** If the 'BIMAsset' is maintained properly, tenderers will be able to view the model when bidding for the work and will have enhanced confidence enabling the tender to be priced without 'risk pricing'.

- **Enhancing Compliance**: by ensuring the CAFM system is integral with the 'BIMAsset' the risk of statutory obligations being missed can be avoided.

2.3 VALUE OF THE 'BIMASSET'

Essentially, managers need to ensure that all elements of the facility are properly documented in the 'BIMAsset'. That is, by having inventory of all the basic elements of the facility, building usage, their location and maintenance records. The digital document has to be updated frequently to accommodate further alterations and demolitions.

The evaluation of the 'BIMAsset' value can never be clear-cut because it depends on the overall organisational configuration. This will depend largely on the level of information captured by the organisation. The value in the data will be as a result of accurate forecasting and cost certainty of estimates generated by the system. This can be evaluated with other benefits derived in terms of reduction in cost, rework etc. Value of the 'BIMAsset' will depend on certain circumstances e.g. the level of up-to-date facility information captured. This can be determined using certain valuation techniques like 'performance in use', which is a method used to determine the value of an asset based on benefits for the user (Lemer, 1998). The 'BIMAsset' can be evaluated in relative terms to its condition and derived benefits for the organisation.

Interested buyers can have more confidence in a particular investment by assessing the economic performance of the asset before purchase. This is important because assets are considered to have value if they can generate revenue (Kyle, 2001). The evidence of any potential revenue generation shows the ability of the facility to meet up with current operational and functional requirements of its client. With that, BIM as a complete package could add value to an investment at the disposal (selling) stage of the lifecycle (Munir, 2012). Therefore, a well documented and properly maintained 'BIMAsset' could improve the economic performance of a property/investment.

2.4 SIMILARITY WITH OTHER INDUSTRIES (IN THEORY AND PRACTICE)

Similarities can be found with the IT and manufacturing industries. Theoretically, Lean Production goes in line with BIM methodology. BIM is generally seen as a promising approach that would aid in achieving the principles of lean construction by reducing waste, improving efficiency, enhancing information management and improving communication (Gerber *et al.*, 2010). The work of Khanzode *et al.* (2006) sought to provide a framework that linked BIM to the Lean project delivery by using Virtual Design and Construction technologies. Also, Sacks *et al.* (2009) hypothesized a framework that showed 48 validated similarities between BIM and Lean principles. These supported the notion of high synergy between BIM and Lean. Therefore, BIM is expected to provide the foundation for some of the results that lean construction is expected to deliver (Sacks *et al.*, 2009).

In practice, similarities could be drawn from the manufacturing industry. A similarity to the BIM collaboration process can be found in the Toyota Production System. A vehicle development system called the '*Obeya*' system was developed for the Prius, which is now the new standard for Toyota. The system serves two main purposes, which is information management and on the spot decision making. It enabled project participants to keep track of the project development schedule through the CAD terminals, schedules with checkpoints and other visual management devices. At the end of the programme, a confidential document was forged recording experiences of vehicle development from start to finish in real time (Liker, 2003). The document is relatively similar to the 'BIMAsset', which documents the entire workings of a system throughout its lifecycle.

Another similarity from the manufacturing industry is from the Rolls Royce Company, where they have a similar system to the proposed 'BIMAsset' which is called Optimized Systems and Solutions (OSyS). This Business management solution has enabled Rolls Royce to generate and update business plans, achieve growth in the services business with 20 percent fewer staff, realise 80 percent reduction in queries regarding forecasts, have an integrated financial model, and have better visibility of quality data through a central database. It also gives the company the opportunity to make informed business decisions and to achieve other operational savings by generating frequent KPI reports that enhance the maintenance schedule which reduces number of maintenance visits and eliminates the need for open subassemblies through database verification (OSyS, 2012). In a way, if the 'BIMAsset' can have similar impacts in the construction industry, building operators will benefit greatly from the use this system because it will improve the quality and integrity of forecast data.

2.5 COMPROMISES

Certainly, there can never be any perfect system or methodology and compromises have to be made. The system will largely depend on human input for the overall workings of the system. The ‘BIMAsset’ will greatly depend on the skill of the asset valuation team/advisors, their level of knowledge to understand the data. Finally, the system will depend on the ability of clients, technical advisors and those people who divest to do due diligence or understand what they are buying. The use of BIM is a technologically sophisticated process; therefore, with incompetent users, unstable applications or inadequate management, the entire process can become complicated (Sacks *et al.*, 2009).

3.0 COMPOSITION OF THE 'BIMASSET'

The 'BIMAsset' like all other products requires resources as inputs in order to generate a reliable 'BIMAsset'. In this section we will outline the requirements, process, value, and confidence levels of the 'BIMAsset'.

3.1 REQUIREMENTS

The basic requirements for the development of a 'BIMAsset' include the following:

i. BIM Technologies
ii. Current Facility Configurations
iii. Models
iv. Contractual Structure
v. Asset Coding and Data Maintenance

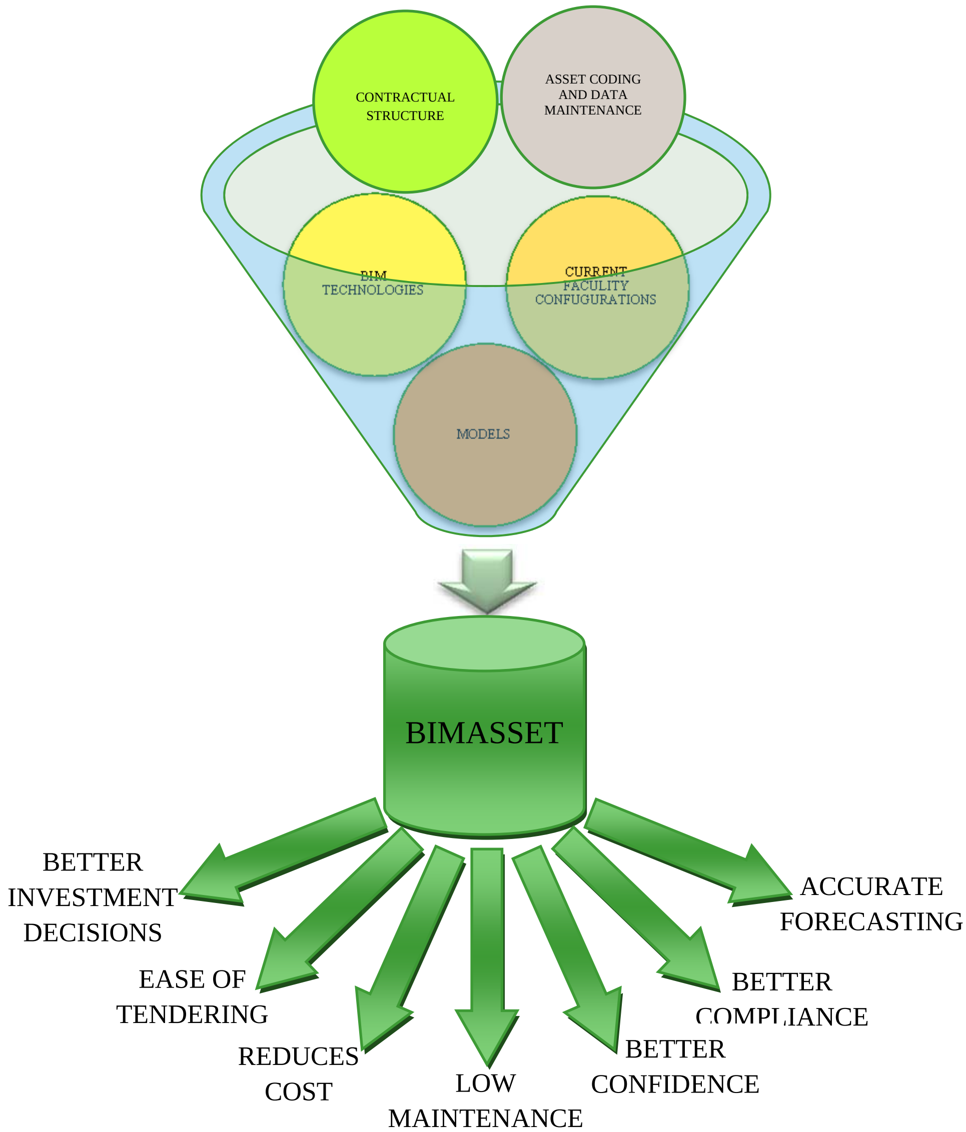

Figure 3: Shows the Composition of the 'BIMAsset'

3.2 CONFIDENCE LEVEL

The confidence level of a 'BIMAsset' depends on the level at which the BIM database is updated. The figure below represents the confidence in 'BIMAsset' depending on how current the BIM dataset is throughout the lifecycle of a facility. This shows that with low confidence in the 'BIMAsset' for a frozen BIM dataset diminishes to a point where the users have no confidence in the data and the BIM investment is lost.

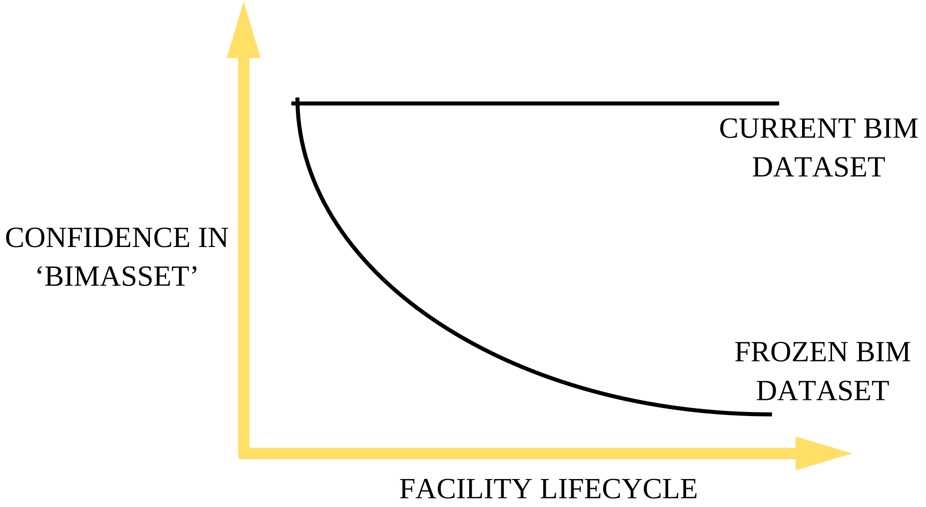

Figure 4: Shows Client Confidence in 'BIMAsset'

The following figure identifies a simple indication of the proportion of the assets replaced for a typical healthcare facility totalling 26 % after a 30 yr period, equating confidence to the proportion of assets replaced over a given period is not appropriate as differing sub components of the 'BIMAsset' data will have differing weightings.

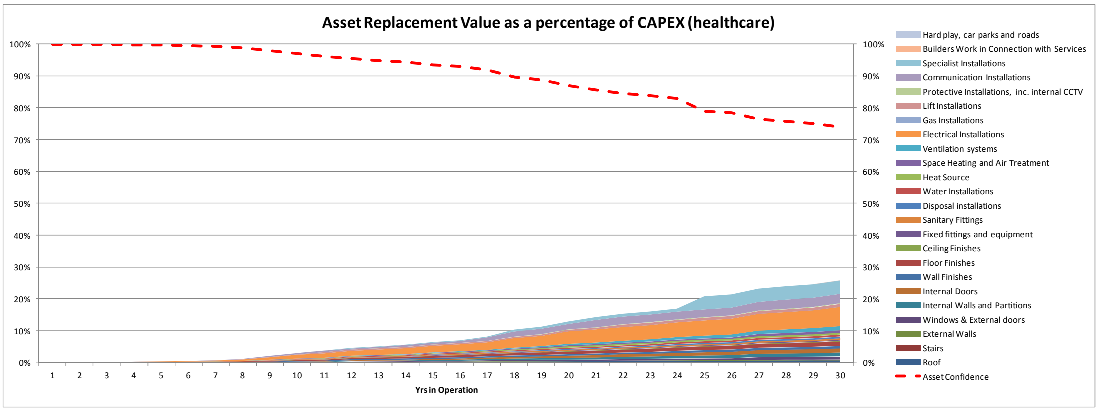

Figure 5: Shows Asset Replacement of a Facility

3.3 PROCEDURE/PROCESSES

This paper proposes some measures for establishing a reliable 'BIMAsset', they are:

- **Contractual Agreements:** Responsibility has to be assigned and stated clearly in the construction contract for managing the BIM data at handover. The contract should stipulate that the FM provider updates the BIM model automatically as part of their contractual responsibilities.

- **Transfer after Construction:** Handover of the BIMAsset at the end of the construction (Soft Landings). Although the handover will have a defined date in the Contractual agreements the handover will be a gradual process where the CAFM implementation develops during the design and is implemented before the completion of construction.

- **Maintenance/Updating:** BIM maintenance should be treated as part of the BIM manager and FM's responsibility. If this method is adopted, both parties with will benefit from the process.

- **COBie/CAFM:** Implementation of the COBie format and selection of the CAFM vendor / operator influenced by their abilities to use / interface with the BIM data this should be a bidirectional link.

3.4 STRENGTHS/WEAKNESSES

The strengths and weakness of the system have to be identified. Some of them are:

- **Complexity:** Implementation of 'BIMAsset' requires significant effort and encompasses many threads including formats, contractual relationships and maintenance.

- **Scale and Asset Type:** Interviews have indicated that the value of 'BIMAsset' is unlikely to be attractive on small scale projects of limited complexity or on commercial developments during the early adopter phase; however on highly serviced high value or high risk assets there is potential

3.5 TYPES OF BIM DATA NECESSARY TO ENHANCE BUILDING OPERATIONS

The following are some of the data which can be derived from the entire BIM process in order to enhance building operations of a facility. Some of them are:

- **Design Data:** Models and supporting calculations for structural and services systems

- **Product information:** Material data, attributes, maintenance obligations and regimes
- **Asset Coding:** Reference and coding structure enabling the interface between the data from the construction phase and the derived data during the operational lifecycle phase.

4.0 CONCLUSION

There are a variety of methods and techniques for making rational asset management decisions in order to ensure effect management of facilities. The ‘BIMAsset’ is seen by the authors as a dataset that could provide some information which clients/managers have never been able to access. This paper highlights the existence of the ‘BIMAsset’ dataset, challenges, compromises, benefits, and how to overcome some of the issues.

The research proposed hypothesis for this study. The interviews and literature review have provided a basis for validating the hypotheses.

- H_1 (Existence and composition of the ‘BIMAsset’): This can be validated from a range of issues reviewed in this study. It is not know whether all the issues regarding composition have been identified in the research. This is because the definition of the ‘BIMAsset’ by the client/manager will determine its full composition.
- H_2 (Confidence level of the ‘BIMAsset’): This could not be validated from the interviews conducted. This is because confidence levels are dependent on many factors which are project specific and are subjective in nature.

As a concluding note, it is the view of the authors that by considering the lifecycle of the BIM data ‘BIMAsset’ there is significant potential to derive enhanced asset value; including financial, time saving and risk / compliance.

4.1 LIMITATIONS

Maintenance of the BIM data and development of the ‘BIMAsset’ is dependent upon considering and establishing the technical and commercial framework at the projects design stages to ensure that it has become fully established before the Asset enters the operational phase of its lifecycle.

4.2 FURTHER RESEARCH

Additional research could be conducted under this topic by taking a survey to determine the confidence level of built assets from building operators. Also, further research needs to be conducted on the analysis of the confidence level of built assets considering that the individual elements of built assets will have different weightings.

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Recent advances in the development of MOST: an open-source, vendor and technology independent toolkit for building monitoring, data preprocessing and visualization

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Abstract:
The present contribution describes approaches for visualizing building related data (temperature, energy use, etc.). A web based visualization framework is presented and a number of use cases are demonstrated (i.e. three-dimensional building browsing). Usability is optimized for diverse screen sizes, input methods (i.e. touch screen), and application logics. Finally, guidelines for further user interface development are presented.

Keywords:
Building management system, monitoring, building data visualization, toolkit, MOST

1. Introduction

The present research is based on a vendor and technology independent toolkit for building monitoring, data processing and visualization. On the one hand this Monitoring System Toolkit (MOST) focuses on the maintenance of a comprehensive data collection, real time data access and the integration of data preprocessing and aggregation techniques. On the other hand diverse software interfaces enable multiple applications to process desired data streams. This paper focuses on one possible processing application, a web-based user interface, which visualizes building information and enables human interaction. The web offers the opportunity to access multiple, spatially distributed physical and virtual data sources in a standardized way. The presented visualization platform

- supports multiple interaction devices (mouse/keyboard, touch, gestures),
- provides reusable user interface elements (charts, menus, etc.),
- separates diverse use cases in different modules and includes a number of prototypical implementations.

Previous work covers real-time building data collection (Zach et al. 2012a), preprocessing and data aggregation (Zach et al. 2012b), and the investigation of possible use cases (Chien et al. 2011).

1.1. Approach

The aim of this work is to build a web based application that provides access to the proposed building monitoring toolkit. Using a prototypical implementation, usability tests are examined. Figure **1** shows the three-layer software architecture of the proposed web interface. On the top level, the user primary interacts with the graphical interface via drag and drop actions. The interface increases intuitive operation by highlighting areas where operations can be performed on dragged objects. Underneath, application logic is separated into modules that can reuse graphical elements of a generic library (*MenuWidget*, *DatapointWidget*, etc.). Operations are supported by control instances that connect graphical elements to certain logic (*ModuleCtrl*, *DndCtrl*, etc.). All communication to the monitoring server is covered within the abstraction layer.

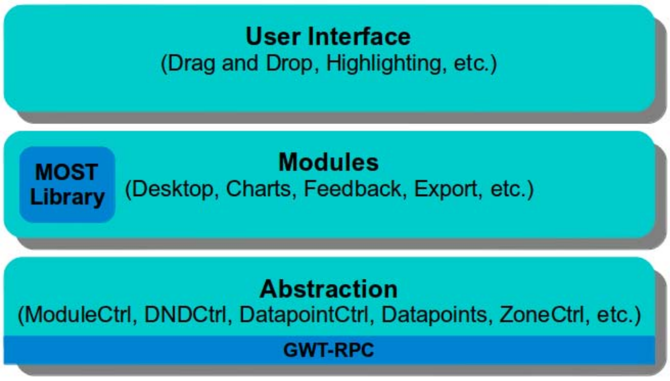

Figure 1. MOST client side framework layers

2. Visualization framework

To enable platform independent user interface development, web based technologies can be used. Furthermore, web frameworks (JSF, GWT, etc.) simplify development by abstracting specific web technologies. The Google Web Toolkit (GWT) was chosen for implementing the proposed visualization framework. GWT enables web development by using the programming language Java for server (running on a central server station) and client side code (running in the user's browser). Client side code is converted to platform optimized JavaScript at compile time. The overall framework focuses on the following design principles (Dix 2004):

- Useful (appropriate functionality)
- Usable (user is able to perform tasks)
- Used (attractive and available).

2.1. Modules

Independent modules can be used to implement different use cases within the visualization framework. All modules are controlled by the class *ModuleController* as shown in Figure **2**. Each module must implement the Java interface *ModuleInterface* and the abstract class *ModuleWidget*. The *ModuleInterface* defines certain meta-data, which provide module specific information (module name, URL, etc.). The graphic representation derives from the abstract class *ModuleWidget*. Each module is instantiated once by the *ModuleRegistrator* class at runtime. During this process, authentication and security procedures are executed.

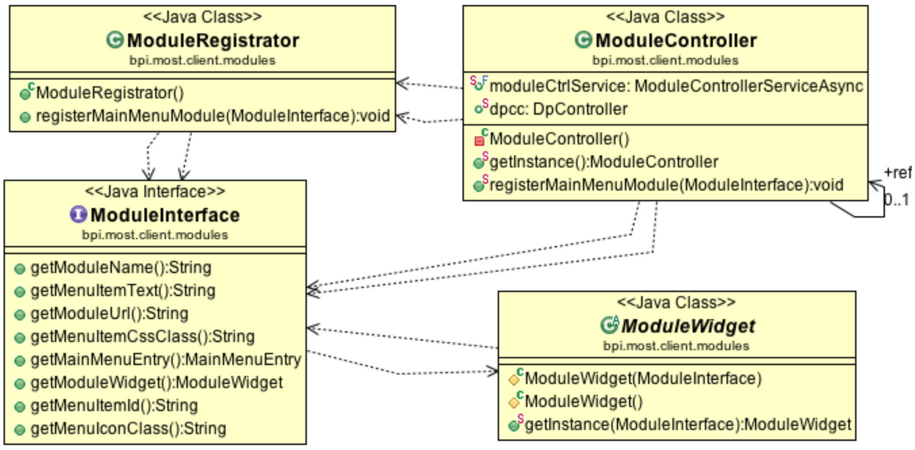

Figure 2. Module registration process

2.2. User interface library

The proposed user interface library provides various components for simplifying module development and building platform and input optimized user interfaces. Nielsen and Molich (1990) state that human-computer interaction is error prone and that the user should be supported when making a decision. Including these premises, the application restricts and guides the user input with two mechanisms, drag and drop and highlighting. User input applies drag and drop as the primary interaction method. Interaction processes become more dynamic and intuitive. By visually highlighting droppable areas the user's choices are limited to valid options. By eliminating erroneous interaction possibilities the application design is improved according to Nielsen's ten usability heuristics (Nielsen 1994).

The proposed library consists of graphical components and logical elements (see Figure **3**). Components are classes, which provide a graphical representation (i.e. *xxxWidgets*). Logical elements are classes, which include no graphical part, but diverse application functionality (i.e. *DragInterface*). The library is based on native GWT features and can be integrated in any GWT project.

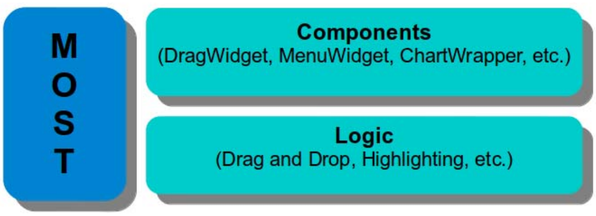

Figure 3. User interface library

2.3. Drag and drop

All available widgets natively support the introduced drag and drop mechanisms (see Figure **4**). The class *DNDController* implements highlighting by adding and removing Cascading Style Sheets (CSS) information from the Document Object Model (DOM). Each *DragWidget* contains information about compatible *DropWidget*. The *DNDController* constantly listens for drag and drop operations and highlights respective *DropWidget* on demand. Each GWT element can be used with the proposed drag and drop features by extending the class *DragWidget*. Several reusable user interface objects are provided within the library (menus, windows, etc.) to unify the user interface design.

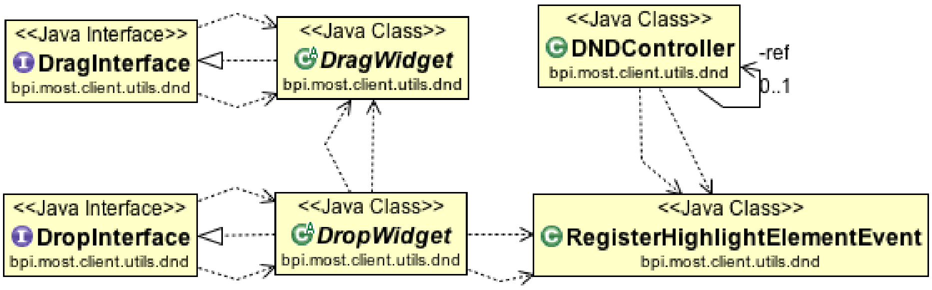

Figure 4. Drag and drop logic

Following these design principles, the visual implementation is separated from the application logic. Figure **5** shows the proposed drag and drop/highlighting feature in a showcase application.

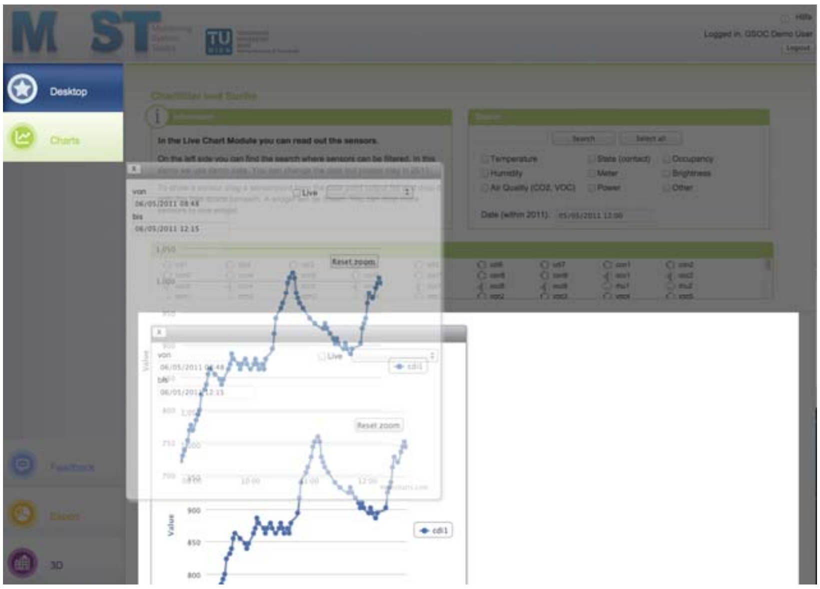

Figure 5. Drag and drop/highlighting procedure

3. Application Modules

To show the potential of the visualization framework, some modules covering various use cases were implemented. For example, the module “3D-Viewer” is provided to map available information points (datapoints) within a three-dimensional model of a building. Furthermore, the “Chart Module” can be used to plot a trend chart of a desired datapoint. A “Desktop” module is available to accomplish different information sources on a central page (similar to the Microsoft Windows Desktop). Diverse objects can be exchanged between modules using drag and drop operation. When dropped on predefined areas, the corresponding module’s specific code processes the incoming information. Figure **6** shows an exemplary use case. First a desired datapoint is found within the 3D-Viewer. Then, a trend chart is generated by moving the respective datapoint to the Chart module (a). Finally, the resulting chart is moved to the Desktop module (b).

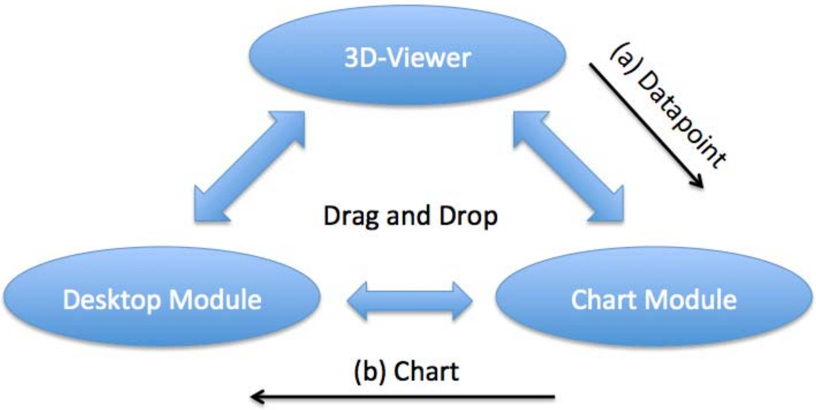

Figure 6. Inter-module communication process

3.1. 3D-Viewer

The module “3D-Viewer” visualizes a three-dimensional building model and respective datapoints based on the platform independent Web Graphics Library (WebGL). WebGL provides a 3d rendering engine supported by all current web browsers. Prototypical implementations have been examined by adapting the projects IFCwebserver 2012 and BIMsurfer 2012. IFCwebserver 2012 uses the WebGL based SpiderGL 2012 library, supports the COLLADA 2012 file format. It showed various disadvantages during tests with building related models (performance issues, large model size, unstructured code, etc.). BIMsurfer 2012 extends the WebGL based SceneJS 2012 library, uses a JavaScript Object Notation (JSON) based file format. It showed appropriate performance characteristics. Therefore, BIMsurfer 2012 was chosen to be enriched with building monitoring related features. The following use cases were investigated for the “3D-Viewer” module:

A. Lead the user within the three-dimensional building model to a desired datapoint
B. Show the user the location of a particular datapoint
C. Visualize critical information of datapoints (i.e. errors)

To lead the user to the desired datapoints in an intuitive way, additional building model browsing features were implemented. For example, building stories can be exposed using a slider bar as shown in Figure **7**. If no building story is marked, all levels are shifted. If a single floor is selected, only this one is exposed. Furthermore, the transparency of the building walls can be controlled with an additional slider bar. The building model is described within a hierarchically structured JSON file. Each building element (door, wall, etc.) is represented as a SceneJS node. Exposing works by translating a node and the children of the respective node along the y-axis by a specific value. Inserting and removing transparent nodes into the building tree changes the transparency of all child nodes. The developed BIMSurfer fork is integrated into the proposed framework by injecting the JavaScript code into GWT code at runtime.

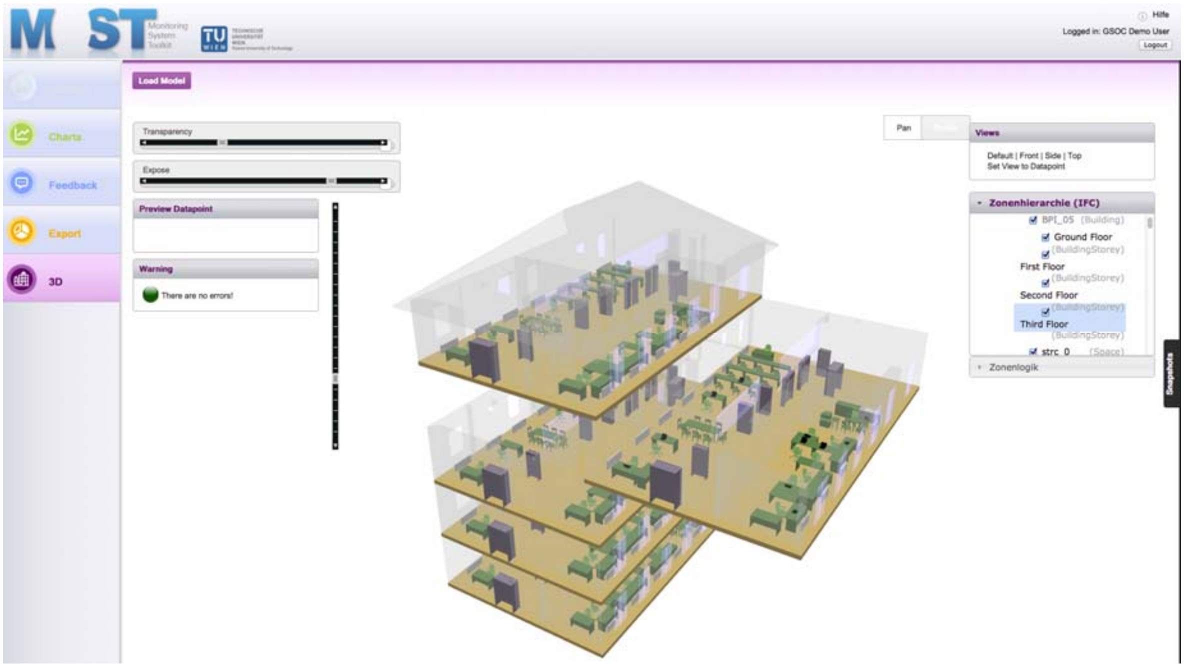

Figure 7. 3D-Viewer module interface

Use case B (show the location of a particular datapoint) is supported by dynamically moving the view to the location of a requested datapoint. The implementation is based on the snapshot feature of BIMsurfer 2012. When dropping a datapoint object on the 3d model, the viewer automatically centers the view on the desired node. Use case C (Visualize critical information of datapoints) is prepared but still under development. It is intended to load warnings of datapoints, within the visualized building model cutout, on demand.

To create a building model for the 3d viewer, any Computer-Aided Design (CAD) software, which supports the export of IFC2x4 2010 (Industry Foundation Classes) compatible files, can be used. Since the CAD application deployed did not support *IfcSensor* and *IfcActor* objects, a naming convention based approach was used to link IFC objects to respective datapoints. Any IFC object using the syntax “dp_<datapoint name>” is processed as a datapoint in the 3D-Viewer (preview on click, drag and drop support, etc.). To convert the IFC file to the required JSON format, BIMserver 2012 is used.

3.2. Chart module

The chart module enables creating trend charts from any datapoint by dropping it on a defined area in the module. Highcharts 2012 is used within a *GeneralDragWidget* as shown in Figure **8**. To enable the visualization of timeframes containing a critical amount of measurements with the highcharts library, the number of shown values needs to be reduced due to performance limits. Therefore, the data preprocessing methods - provided by the MOST toolkit - are used to calculate a reduced number of values on demand. Before drawing a chart, the amount of measurements in the requested timeframe is analyzed. If a critical amount of measurements is exceeded, data preprocessing algorithm (Zach et al. 2012c) are used to request a temporally set of data (periodic values) with a reduced amount of values. Finally, the preprocessed data is drawn in the chart. If the user zooms into the chart, new values are requested the same way. This strategy reduces the high amount of measured data in a transparent manner. It shows how the data preprocessing functionality can be used to simplify application development. Via the proposed drag and drop approach, new datapoints can be dragged from various source modules (chart, 3D-Viewer, etc.) and dropped on an existing chart. The chart includes the new source automatically. Enabling the live feature triggers the server to push new values to the web interface and to include them in the existing chart.

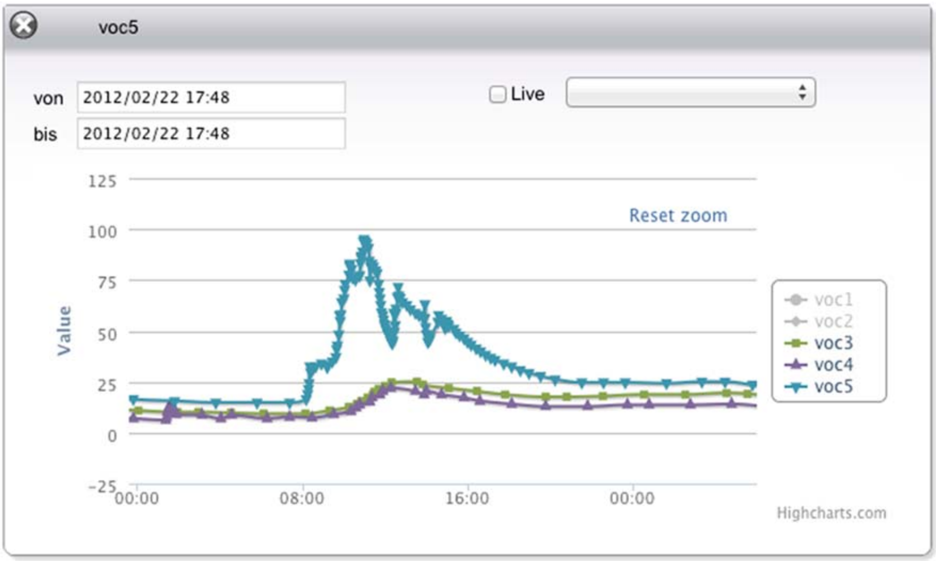

Figure 8. *DragWidget* object containing a chart with multiple datapoints

4. User Interaction

The user interface was optimized for three different types of user input technologies, to support a wide range of devices and to broaden the range of use cases. These user interface types include established methods (mouse/keyboard and touch input) and one upcoming technology, the gesture input (natural interaction). The target output devices are tablets, desktop PCs, and information screens (i.e. touchscreen or beamer).

4.1. Input Interaction

To enable similar interaction processes for all input devices, the following operation types are defined:

- Select/activate
- Drag
- Pan/rotate
- Zoom

Select and drag operations build the basis for all interaction processes. Pan, rotate, and zoom are advanced input methods, which are only required in certain cases (i.e. 3D-Viewer) and are not natively supported by all input devices. Table 1 to 4 show how diverse interaction operations are implemented with different input devices.

Table 1: Interaction type select/activate

Input device	**Interaction**
Mouse/ keyboard	Clicking
Touchscreen	Tapping
Gesture input	Push gesture (the hand is moved in the direction of the sensor like pushing an imaginary button before the user)

Table 2: Interaction type drag

Input device	**Interaction**
Mouse/keyboard	Clicking plus dragging the selected widget to the target point and releasing it
Touchscreen	Tapping plus dragging the selected widget to the target point and releasing it
Gesture input	Push gesture plus dragging the selected widget to the target point and releasing it

Table 3: Interaction type pan/rotate

Input device	Interaction
Mouse/keyboard	Clicking on the building model plus holding down the mouse button and moving the cursor
Touchscreen	Tapping on the building model plus holding down the tip and moving the cursor
Gesture input	Push gesture on the building model plus keeping the posture and moving the hand

Table 4: Interaction zoom

Input device	Interaction
Mouse/keyboard	Using the scroll wheel of the mouse or two fingers on a track pad
Touchscreen	Single touch: Using a zoom slider. Multi touch: Putting two fingers on the screen and moving them apart/closer together.
Gesture input	(1) Changing the zoom slider in the user interface (2) Moving the body closer/farther from device to zoom in or out (3) Move both hands apart/closer

Pan and rotate functionalities are based on the same interaction procedure. A switch to distinguish between the two navigation modes is implemented within the 3D-Viewer module. Input device based differentiation between pan/rotate is part of future research.

4.2. Usability Guidelines

We intend to conduct a usability study of the user interface environment in the near future. One focus of this study is to generate reusable guidelines for the implementation of touch and/or gestural interaction compatible user interfaces. Therefore, different user groups are tested using the proposed visualization framework. The analysis process is based on the usability engineering lifecycle defined by Mayhew 1999. It includes various steps, which are:

- Requirements analysis (includes persons, task analysis, general design principles and usability goals),
- Design/testing/development (includes wireframes, storyboarding, heuristic evaluation, screen design standards, detailed user interface) and
- Installation setup.

Test users conduct predefined tasks in the proposed application environment. The process is monitored and usability bottlenecks are analysed. Qualitative usability goals for all input devices are

- untrained users are able to select datapoints from the 3D-Viewer,
- users are able to create a chart plot of a datapoint and
- users are able to drag and drop a widget from a module to another one.

By analysing the usability bottlenecks, the user interface can be optimized based on the three points of Dix 2004. It should be useful (functionally), usable (it is easy to do things), and used (attractive and available).

5. Conclusion and future outlook

The proposed framework offers a bundle of components that simplifies the development of dedicated, platform optimized user interfaces. The concept focuses on reusability and usability. Therefore multiple screen sizes and input methods were tested. By conducting a usability study, guidelines will be developed to provide a basis for future user interface design. Core questions are:

- How can interaction operations be ported to the proposed input devices?
- Which input operations are best suited for a specific input device?
- Which constraints (i.e. hardware, driver) must be considered?

6. Acknowledgement

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Strategic Facilities Management Using Public and Private Funding for Energy Projects: A Case Study

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Abstract:
The Alamo Community College District (ACCD) in San Antonio, Texas has a long history of participating in public and private sector loan programs for facilities energy projects. In its most recent experience, the District has demonstrated the value of these loans beyond simple kWh savings. In 2002, The District received $3.0 million in private sector loans for projects including indoor lighting retrofits, cooling tower upgrades, and Continuous Commissioning®. Documented energy cost savings from this project exceeded the projected savings since its completion in early 2005. Now nearly a decade later, ACCD is participating in a State-funded revolving loan program for energy retrofits estimated at $10 million. A wide range of projects are proposed, including indoor *and* outdoor lighting retrofits, central plant upgrades, solar thermal pool heating, enhanced retrofit commissioning and installation of water based thermal storage systems. In addition, existing campus load profile analysis uncovered utility rate change options that yielded instant savings. In total, over $1 million per year in cost savings and 4 megawatts of mitigated power generation capacity are projected due to these projects. This paper presents the details of the loan procurement process as part of a state program designed for building energy efficiency retrofit projects, and how ACCD is using available resources to strategically integrate short-term systems upgrades with long-term infrastructure, energy management, and sustainability goals.

Keywords:
Facilities Management, Energy Loans, LoanSTAR, Thermal Storage, Strategic Planning, Energy Cost Reduction Measures

1. Introduction

It is a well-established fact that energy performance improvement projects can have a significant impact on an institution's overall financial performance and environmental footprint. Steps to improve energy performance can also lead to improved comfort, which positively affects occupant productivity. For many organizations facing economic downturn, revitalizing and expanding energy initiatives can help spur economic activity and reduce operating costs. In the last few decades, funds to finance public and private sector projects have become increasingly abundant. However, barriers such as a lack of understanding for financial and engineering aspects of such funding programs, lack of competent owner's representation, and perceived risks have discouraged widespread participation. ACCD, the subject of this case study, has successfully navigated these barriers over several rounds of energy project funding in order to strategically cut utility costs while stimulating growth even in a harsh fiscal climate.

2. Background

In 2001, ACCD received a preliminary energy assessment report funded by the U.S. Department of Energy (DOE) Rebuild America Program. After reviewing the findings and conducting a competitive bidding process for potential lenders, the District initiated a \$3,076,207 loan program financed by a local bank at 3.84% interest. The basis of the loan was a detailed assessment conducted by Texas Energy Engineering Services, Inc. (TEESI) with Continuous Commissioning® (CC®) portion lead by Texas A&M's Energy Systems Laboratory (ESL). The assessment covered approximately 2,350,000 ft^2 of facility area, comprising four main campuses and two district office buildings in San Antonio, Texas. Proposed Energy Cost Reduction Measures (ECRMs) included: indoor lighting improvements, motion sensors installation, Saint Philip's campus central plant cooling tower upgrade, controls systems upgrades, variable frequency drive and booster pump installation at Palo Alto College, and CC® at all existing locations. ECRMs planning to implementation phase steps included: preliminary energy analysis report, detailed energy assessment (investment grade) report, design and construction management of ECRMs, CC® and Measurement and Verification (M&V). TEESI's scope was design and implementation of approved ECRMs while the ESL was responsible for CC® and conducting M&V for the project. Retrofits were implemented using the traditional Design-Bid-Build approach while commissioning and M&V activities were through inter-agency agreement. The simple payback of individual projects ranged from 3 to 22 years with overall payback projected at almost 7 years. Loan repayment equaled \$3,513,038.76 (\$41,821.89 per month times 84 months). Loan repayment was from January of 2003 through December 2009, and was sourced from savings from the District's utility budget generated by ECRMs. There were no explicit guarantees of energy savings with total reliance on the team experience, proven technology applications, and quality control techniques. The CC® measures were completed in late 2003 while retrofits were completed in late 2004 to early 2005. Measured savings indicated actual payback of 6 years compared to projected payback of almost 7 years. ESL continues to monitor savings and work with ACCD staff to constantly fine-tune the operations of the buildings.

In May of 2012, the ACCD Board of Trustees formally requested the Chancellor to develop, manage, and direct the District's Sustainability Program. The sustainability mission of the District is "meeting our needs today while ensuring that future generations retain the ability to meet their needs". ACCD embraced environmental, social and economic sustainability by making provisions and taking responsibility for its decisions and actions. The program will integrate the values of sustainability, stewardship, and resource conservation in the way that it interacts with the physical environment and community. The program emphasizes embracing sustainability for existing buildings' maintenance and operations, and renovation projects. To this end, the District will establish seven environmental sustainability areas of concentration: Sustainability Literacy, Energy, Air Quality, Waste Management, Water, Facility Maintenance, Renovation and Construction, and Purchasing.

In anticipation of adopting this program, ACCD facilities management department initiated a preliminary energy assessment to identify opportunities for upgrading equipment and infrastructure while further improving energy efficiency. The findings were included in the application submitted for a competitive loan procurement program as administered by State Energy Conservation Office (SECO). The newly proposed ECRMs were divided into two phases of detailed assessment and loan procurement: Phase I in 2011 and Phase II in 2012. Detailed assessments covered a total of 4.3 million ft^2 in San Antonio including a recently added main campus. Selected ECRMs will greatly impact ACCD's energy efficiency and help achieve its goals in the short as well as long term.

3. Facilities Description

The ACCD locations selected for projects included San Antonio College, Saint Philip's College, Southwest Campus, Palo Alto College, Northeast Lakeview College, Northwest Vista College, and two District Office locations. Table 1 summarizes the primary energy users (lighting and HVAC) at each facility. With the exception of the District Offices and Southwest Campus, most facilities use chilled water (CHW) cooling provided by water-cooled centrifugal chillers. San Antonio College and Northeast Lakeview College each distribute CHW to campus buildings with a single central plant and CHW loop. Northwest Vista College serves buildings from two separate central plants, but on one common loop. Palo Alto College also uses two plants, but a valve system can isolate a separate CHW loop for each if desired. Finally, St. Philip's College has a new section of campus served by a separate chiller plant and distribution loop. The new plant at St. Philip's uses variable primary pumping, while all other plants have constant primary, variable secondary systems. On the air side, the vast majority of units are single or dual duct variable air volume (VAV) air handling units (AHUs), with some single zone units for areas such as gymnasiums and theatres.

Table 1. ACCD Facilities Summary.

Campus	Approx. Square Footage	Indoor Lighting	Outdoor Lighting	Cooling	Heating	Primary Air Distribution
San Antonio College	1,587,000	T8 fluorescents and metal halides	HID pole lights and wallpacks	Four 1,000 ton water cooled chillers	Five 4,000 MBH steam boilers	Single and dual duct VAV AHUs with fan powered boxes
Saint Philip's College	785,000	T8 and T5 fluorescents and metal halides	HID pole lights and wallpacks	Seven 500 ton water cooled chillers	Three 8,370 MBH steam boilers	Single duct VAV AHUs with fan powered boxes
Southwest Campus	385,000	T8, T5, and T12 fluorescents and metal halides	HID pole lights and wallpacks	Rooftop units, split-DX and two 180 ton air cooled chillers	Electric and gas furnace, one 1,000 MBH HW boiler	Single duct VAV AHUs, RTUs
Palo Alto College	553,000	T8 fluorescents and metal halides	HID pole lights and wallpacks	Five 500 ton water cooled chillers	Electric terminal reheat and three 4,123 MBH HW boilers	Single duct VAV AHUs with fan powered boxes
Northeast Lakeview College	464,000	T5 fluorescents and metal halides	HID pole lights and wallpacks	Three 800 ton water cooled chillers	Electric terminal reheat	Single duct VAV AHUs with fan powered boxes
Northwest Vista College	588,000	T8 and T5 fluorescents and metal halides	HID pole lights and wallpacks	Four 500 and two 375 ton water cooled chillers	Electric terminal reheat	Single duct VAV AHUs with fan powered boxes
District Office, Houston Street	33,000	T8 Fluorescents	HID pole lights and wallpacks	Rooftop units and split-DX	Electric and gas furnace	Rooftop units and split-DX
District Office, Sheridan Street	44,000	T8 Fluorescents	HID pole lights and wallpacks	Rooftop units and split-DX	Electric and gas furnace	Rooftop units and split-DX

4. LoanSTAR Revolving Loan Program

The Texas LoanSTAR (loans to Save Texas And Resources) Program is the largest state-run energy efficiency and conservation program of its kind in the United States. The program is administered by the Texas State Energy Conversation Office (SECO). Loan funds are targeted for energy retrofit projects at public buildings throughout the state of Texas. The program was initiated by the Texas Energy office in 1988 and approved by the DOE as a state wide building energy efficiency demonstration program. Original funding of $98.6 million for energy efficient retrofits came from Petroleum Violation Escrow (PVE) funds. As a demonstration program, it went through an extensive data monitoring and evaluation process. During the mid-90's, the demonstration label was removed from the program. During the demonstration phase, Borrowers used traditional Design-Bid-Build project delivery method. In 2001, the program was opened to participation by Energy Savings Performance Contracts (ESPC) and water conservation programs. The success of the program is attributed to the quality control mechanism put in place and the detailed guidelines for the program participants. Table 2 summarizes performance results from program inception through March 2012 (source: SECO).

Table 2. LoanSTAR program results since inception through March 2012

Number of Loans	212
Number of loan defaults	0
Volume of loans	$305,332,224
Cumulative energy savings	$355,762,062
Cumulative emissions savings	11,024 tons Nitrogen oxides, 3,611,090 tons Carbon dioxide, 7,918 tons Sulfur dioxide and 0.05 tons Mercury

The program provides funding for measures that will result in utility dollar savings, not just energy consumption savings. The cost of a detailed energy assessment report can be rolled into the loan amount, if desired by the Borrower. A cumulative simple payback of ten years or less is required, and current single application loan funding limit is a maximum of $5 million per application. Loan repayment schedule is provided to the Borrower when: the project is 100% complete, the project has been approved by the SECO Engineers, the Borrower has received all reimbursements, and SECO has received the Borrower's Final Report.

The principal amount on the Loan Repayment Schedule consists of the dollars reimbursed plus the interested accrued on the reimbursed dollars. Each time a Borrower requests a reimbursement during construction, interest begins to accrue on the amount reimbursed. Interest rates under the program range from 2.5% to 3.0%. Interest will continue to accrue up to the day of the first loan payment. Repayment of loan starts 90 days after the project official closeout. As loans are repaid by the Borrower(s) the money is returned to the program to make additional loans, making it an ongoing or "revolving" funding program.

5. ECRMs (Phase I and II)

Due to maximum loan amount limitations per application, ACCD's recent funding procurements were divided into two phases. Phase I is currently in the design and construction phase with a loan of $4,999,975 for projects including indoor lighting upgrades, central plant upgrades, solar pool heating, and thermal energy storage. Phase II funding has recently been approved and is entering the design and construction phase, with a loan of $4,815,464 for projects such as outdoor lighting upgrades, thermal energy storage, controls upgrades, and enhanced commissioning. Both phases have a projected completion timeline of 12-18 months. The project costs and savings presented in the sections that follow are based on utility dollar savings only and do not include potential maintenance savings or rebates from the utility provider, with the exception of rebates included in the proposed thermal storage projects.

5.1. Phase-I ECRMs

Table 3 summarizes the energy, environmental, and financial impact of Phase I projects. A brief description of each proposed Phase I measure follows.

Table 3. ACCD LoanSTAR Phase I Project Summary.

SUMMARY OF PROJECT (Phase I)		
	Total	
kWh Savings	6,481,548	kWh/yr
Demand Savings	19,977	kW-mo/yr
Gas Savings	6,036	MCF/yr
Total MMBTU Savings	28,332	MMBTU/yr
Utility Cost Savings	**$498,421**	**$/yr**
Base Year Cost Reduction	8%	%
Est. Annual Greenhouse Gas Emission Reduction (CO_2)	**4,662**	**Tons**
Est. Mitigated Power Generation Capacity	**2.1**	**MW**
Implementation Costs	$4,999,975	$
Simple Payback	10.0	Years
LoanSTAR Interest Rate	**3.00**	**%**

Interior Lighting Retrofits: This project comprised a retrofit of existing light fixtures by replacing all 32 W, T8 lamps with 28W, extended life T8 lamps. Fixtures were located throughout the buildings in hallways, offices, conference rooms, classrooms etc. Savings calculations were based on manufacturers published wattage levels and observed operating hours, with adjustments for heating penalty and cooling savings. Implementation costs were based on current vendor quotations at quantities corresponding to district-wide fixture retrofits. Costs included lamp and ballast disposal per Federal and State guidelines. Across all the ACCD campuses, projected costs and annual utility savings for this project were $794,327 and $101,054, respectively, yielding a simple payback of 7.9 years.

High Bay Lighting Retrofit: It was also recommended to replace existing HID light fixtures in gymnasiums, mechanical/electrical rooms, and other areas with 32W, T8 high bay linear fluorescent lamps and fixtures with high ballast factor (>1.15) ballasts. Savings calculations were based on manufacturers' published wattage levels, and implementation costs were based on current vendor quotations. Costs included lamp and ballast disposal per Federal and State guidelines. Across all the ACCD campuses, projected costs and annual utility savings for this project were $322,197 and $61,310, respectively, yielding a simple payback of 7.9 years.

Central Plant Upgrades - San Antonio College (SAC): The central plant at SAC will undergo a major retrofit involving chillers, cooling towers, pumps, hot water generation system and controls upgrade. Two out of three existing 1,000 ton chillers were recommended for replacement with new high efficiency units. The existing wooden cooling tower for these chillers (chillers and cooling tower installed in 1991) were also recommended for replacement. Savings calculations for these projects were based on cooling load bin hour analysis in conjunction with manufacturer's data for chiller part loading, as shown in Figure 1. Equipment performance requirements will be enforced through guide specs, formal submittals and certifications. The projected costs and annual savings for this project are $1,586,760 and $151,393, respectively, yielding a simple payback of 10.5 years.

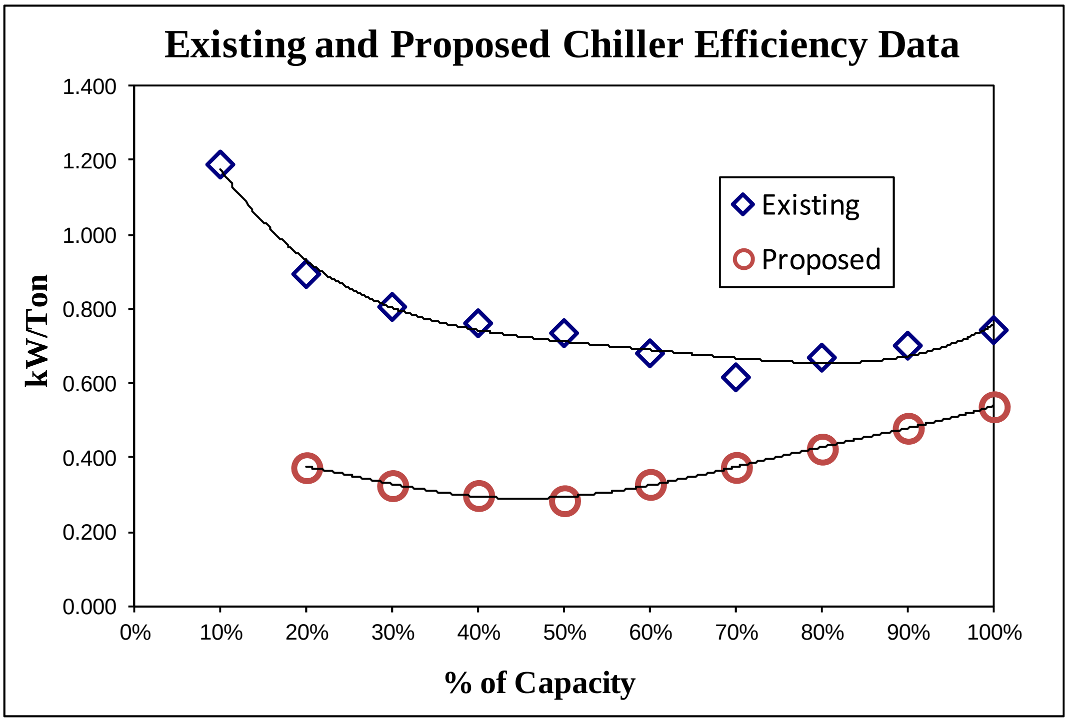

Figure 1. SAC Chiller Part Loading Data Used in Savings Calculations.

As part of the chilled water (CHW) system upgrades, it was also recommended to install variable frequency drives (VFDs) on four primary chilled water pumps to modulate the pump speed as required by the chiller load. In addition, it was recommended that flow restriction devices such as triple duty valves be removed from both primary and condenser water (CW) loops, and that VFDs be installed on condenser water pumps to balance flows to design levels under the new optimized pump head. The anticipated costs and annual savings for this project are $125,232 and $34,320, respectively, giving a simple payback of 3.6 years.

The existing SAC boiler plant comprises five 4,000 MBH steam boilers. Each steam boiler is equipped with a steam-to-hot water heat exchanger. This project proposes to replace the existing steam boilers and associated heat exchangers with four new high efficiency 4,000 MBH hot water boilers and two 2,000 MBH condensing hot water boilers with upgraded controls. The project scope included turnkey installation and removal/disposal of old existing equipment. The estimated costs and annual savings for these central plant upgrades is $558,227 and $30,503, respectively, giving a simple payback of 18.3 years.

Solar Thermal Pool Heating System Installation -SAC: This project involved installation of a solar collector pool heating system to supplement the existing pool boiler at the Candler Physical Education Center. The solar collection system was to provide a first stage of heating for the pool, with the natural gas fired boiler used as a second stage when needed. The anticipated costs and annual savings from this project are $87,048 and $5,793 respectively, giving a simple payback of 15 years.

Install Thermal Storage System (TSS) - Northeast Lakeview College: This project involved installing a water based Thermal Storage System (TSS) to shift the cooling demand from on-peak periods to off-peak periods. The "cooling" demand to be shifted includes the chiller kW, primary and condenser pump kW and the cooling tower fan kW. The system will use existing chiller capacity, and the storage tank will be located adjacent to the physical plant. Piping will be added to connect the chillers and the storage tank system. The capacity of the proposed storage tank (approx. 9,000 ton-hrs, 1,000,000 gallons) was calculated based on the peak kW-profile for the highest demand day of the year, while the potential savings were calculated based on the peak profile for the highest demand day in each month. These profiles were determined from central plant trend data taken from the campus control system. An example of an observed peak day in August of 2011 is shown in Figure 2. These profiles were confirmed with 15-minute interval data from the utility provider.

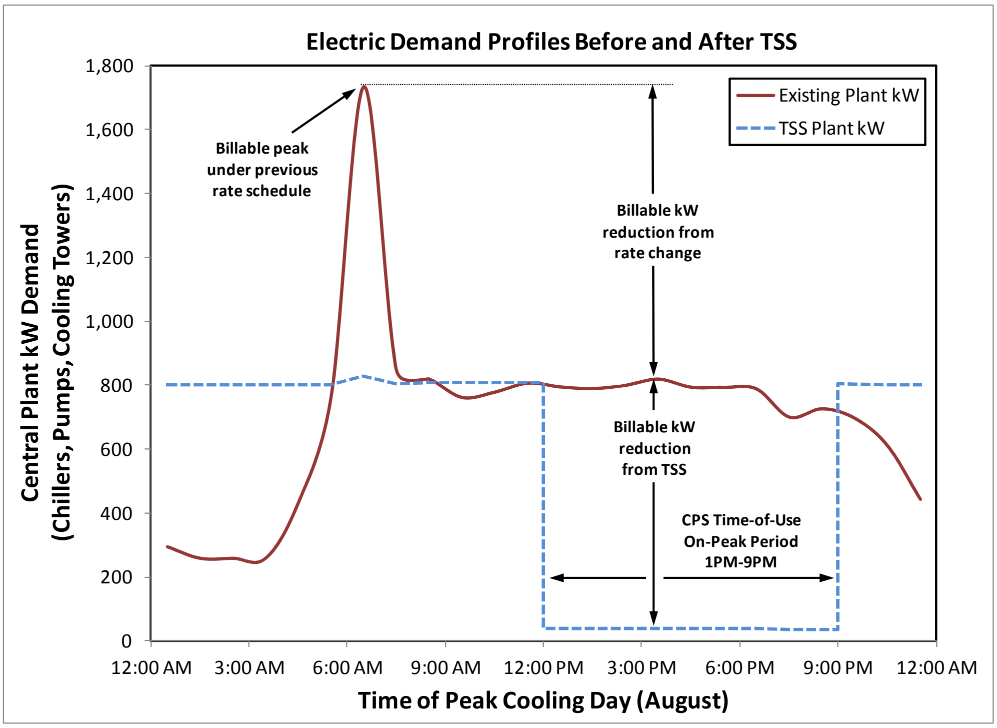

Figure 2. Peak load profile from central plant trend data.

The TSS will store chilled water at 40°F (colder supply will maximize capacity) in the evening between 11 PM and 7 AM, for campus cooling use during the utility company “City Public Service” (CPS) demand window from 1 PM to 9 PM. The plant demand will be minimal (secondary pumps only) during this entire peak time (i.e., this is a full-shift design).

In addition, existing system flow restrictions (flow regulating devices, etc.) will be removed and VFDs installed on the primary chilled water pumps. Existing condenser water pumps were determined to be oversized for the application. The new CW pump will be selected with a larger impeller and smaller, slower premium efficiency motor, still meeting flow and head requirements. Primary pump VFDs will be used to vary flow through the chillers as needed to maintain optimum leaving water temperature at the optimum chiller load.

To fully realize savings from the TSS, the NLC campus will be switched to CPS's time-of-use rate. From an analysis of current consumption and demand at NLC, it was determined that the facility could benefit from a rate change with no capital retrofits required. The utility cost savings during the interim period before completion of the TSS project were included in the ECRM. In addition, NLC was found to be eligible for a "High Voltage Discount" of $0.39/kW. The utility rate change modeling and impact was discussed and verified with the utility. The new rate is already in place and saved nearly $15,000 through two months (January-February of 2012) when compared to "what-if" billing using the previous rate schedule. The thermal storage project has an anticipated cost and annual savings of $1,526,184 and $114,049, respectively, yielding a simple payback of 13.4 years.

5.2. Phase –II ECRMs

Table 3 summarizes the energy, environmental and financial impact of Phase II projects. A brief description of each proposed Phase II measure follows.

Table 4. ACCD LoanSTAR Phase I Project Summary.

SUMMARY OF PROJECT (Phase II)		
	Total	
kWh Savings	6,708,533	kWh/yr
Demand Savings	24,320	kW-mo/yr
Gas Savings	2,553	MCF/yr
Total MMBTU Savings	25,519	MMBTU/yr
Utility Cost Savings	**$481,851**	**$/yr**
Base Year Cost Reduction	9%	%
Est. Annual Greenhouse Gas Emission Reduction (CO_2)	**4,603**	**Tons**
Est. Mitigated Power Generation Capacity	**2.0**	**MW**
Implementation Costs	$4,815,464	$
Simple Payback	9.99	Years
LoanSTAR Interest Rate	**2.50**	**%**

Outdoor Lighting Retrofits, Multiple Campuses: This project involved retrofitting existing light fixtures by replacing Metal Halide (MH) exterior lighting with suitable induction lamp retrofits reusing the existing housing. Fixtures are located throughout the campus in parking lots. The projected costs and annual savings for this project are $576,906 and $40,658, respectively, giving a simple payback period of 14.2 years.

Install TSS System Palo Alto College and Northwest Vista College: Similar to the TSS for Northeast Lakeview in Phase I, this project scope includes construction of a water based thermal storage tank with related piping, as well as installation of pump VFDs to balance primary and CW flows with optimized pump heads. In the case of Northwest Vista College, the proposed tank was sized to mitigate the load of one of the two NVC central plants only

(Texas Persimmon Plant). At Palo Alto, space limitations led to a constrained tank size, from which the potential load shift was back-calculated (i.e. a partial storage design). Both campuses, and especially PAC, currently have issues with low CHW system ΔT (as low as 6°F on average at PAC when designed for 10°F). In order to maximize the cooling capacity of the proposed TSS tanks, and thus the potential for load shift, solving or improving the low ΔT will be part of the project. In addition to providing colder water from the tanks, zone pressure regulation valves will be installed at buildings nearest to the central plant to restore coil controllability and prevent control valve blow-through. Other possible causes will be investigated as part of a proposed enhanced commissioning program. With these changes in effect, the system ΔT is expected to achieve 12-16°F or more with the TSS in place. The Phase II TSS projects have a projected cost and annual savings of $2,696,497 and $158,427, respectively, yielding a simple payback period of 17 years.

Enhanced Building Commissioning: This ECRM proposes an enhanced commissioning program that will supplement and build on the CC® measures that was initiated over eight years ago and that is currently on-going. The proposed ECRM will combine aspects of controls optimization, retro commissioning, specs for repair and minor retrofits and design/construction phase commissioning for TSS and other new systems. It will include new measures focusing on load management and enhanced demand controls, as well as repair and retrofit projects such as VFD installation. The ECRM is expected to be a key component of ensuring that overall projected savings for both phases are realized. The proposed program has a projected cost of $958,789, which includes a $248,789 allowance for minor repairs and upgrades as well as air-handler VFD installations. The estimated yearly savings is $265,441, giving a simple payback period of 3.6 years.

EMS installation at Northeast Lakeview College, Building 7990: This ECRM comprised installation of an EMS interface with five Rooftop Units (RTUs) at a satellite building for NLC. Savings were calculated from avoided operating hours due to resultant scheduled start/stop capabilities, as well as cooling energy savings from potential remote setbacks and setpoint limitations. The anticipated costs and annual savings of the project are $17,315 and $3,306, respectively, yielding a simple payback of 5.2 years.

EMS upgrade- Northeast Lakeview: This ECRM proposed to tie an input signal from motion sensors installed in spaces to existing VAV box demand setup/setback functions. When spaces are unoccupied, setpoints will be reset up 3 degrees in cooling and down 3 degrees in heating, saving on fan energy as well as cooling/heating energy during unoccupied periods. The upgrade will also aid in the ability to reset ventilation amounts based on actual sensed occupancy on respective units. The projected costs and annual savings from this project are $186,591 and $14,018, respectively, giving a simple payback period of 13.3 years.

6. Savings Summary

Figure 3 shows the cumulative savings from the commissioning and retrofits performed as part of ACCD's initial energy loan from 2002 to September 2011.

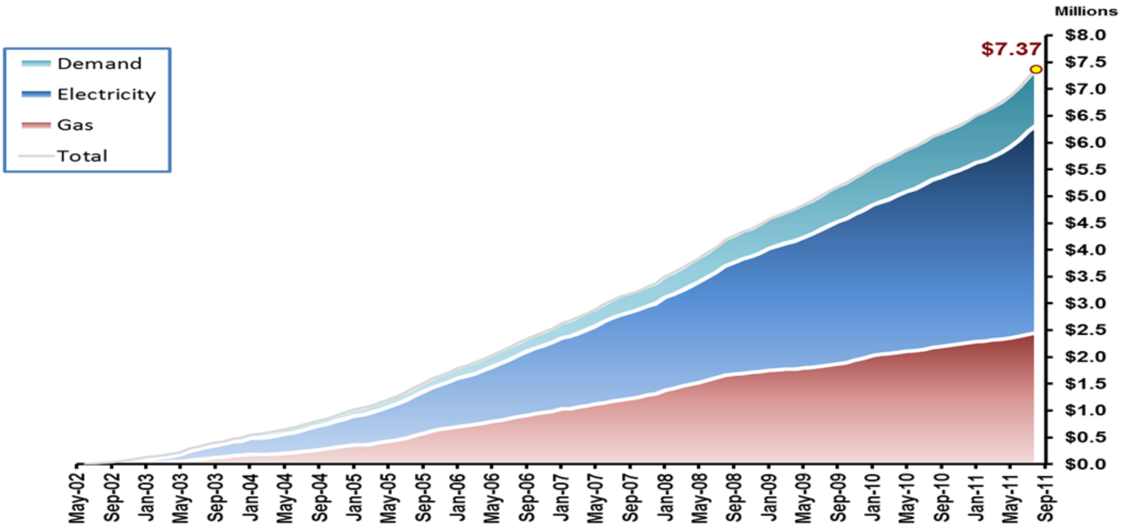

Figure 3. Estimated savings from CC measures (Courtesy Energy Systems Lab).

The experience with and success of the previous program shown above played a pivotal role in the District's decision to pursue additional energy retrofit programs. The recent adoption of a District-wide sustainability plan set a goal to reduce energy use by 20% from the base year (August 2011 to August 2012) while also reducing the Colleges' carbon footprint. The Phase I and II ECRMs, as summarized in Table 5, are expected to contribute significantly toward these economic and environmental goals.

Table 5. Phase I and II ECRMs Summary

SUMMARY OF PROJECT (Combined Phase I and II)		
	Total	
kWh Savings	13,190,082	kWh/yr
Demand Savings	44,297	kW-mo/yr
Gas Savings	8,589	MCF/yr
Total MMBTU Savings	53,851	MMBTU/yr
Utility Cost Savings	**$980,273**	**$/yr**
Base Year Cost Reduction	17%	%
Est. Annual Greenhouse Gas Emission Reduction (CO_2)	**9,265**	**Tons**
Est. Mitigated Power Generation Capacity	**4.1**	**MW**
Implementation Costs	$9,815,439	$
Simple Payback	10	Years

In addition to the energy consumption and greenhouse emissions savings possible from this program, Alamo Colleges will also be able to take advantage of other long-term benefits, such as mitigating equipment replacement, maintenance, and repair costs. The fast paybacks of measures such as lighting retrofits, CC®, and enhanced commissioning make possible larger infrastructure upgrades such as chiller and boiler replacements. Other projects like thermal storage, whose cost savings are not as immediate, represent an investment in the next 30+ years by the district, when energy *demand* is anticipated to be a larger component of utility costs. In addition, the system will enable participation in demand response programs and provide standby cooling capacity if needed.

In addition to energy and demand cost savings, the Phase I and II projects also offer other cost benefits such as utility rebates. Utilities offer standardized rebates for lighting and HVAC upgrades, while custom rebate programs are available for other technology such as TSS. Up to $850,000 in rebate opportunities are anticipated from standard offers alone. For TSS in particular, TEESI will negotiate with CPS to incorporate extended monitoring for five years or more to verify electrical load reduction. The resultant real-time metering by the utility may identify additional opportunities.

7. Conclusion

ACCD, as a public institution, has utilized both public and private sources of funding for energy efficiency project implementation. By adopting a District sustainability plan, with particular emphasis on energy consumption reduction, top management has shown its commitment to sustainability and long-range strategic planning. By undertaking longer payback thermal storage projects, ACCD is positioning itself to absorb anticipated higher future demand costs. A projected 4 MW of peak demand reduction represents utility cost savings for the District as well as mitigated generation capacity for the utility provider. Shorter payback programs such as commissioning make longer payback projects possible and act as a quality control and assurance to verify goals are being met.

Availability and access to public and private loan funding programs can play a vital role in providing facilities management departments a means to upgrade aging equipment through a stream of energy savings. Unfortunately, obstacles such as economic uncertainties and perceived risk often discourage participation. Careful selection of a technical team to represent Owners throughout the process and clear but flexible loan program guidelines are all critical to overcoming these hurdles. As demonstrated by Alamo Colleges, strategic and experienced use of energy loan programs can help reduce operating costs and spur economic development while positively impacting the environment.

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Micro Level Data Analysis in Continuous Commissioning®: A Case Study

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Abstract:
The overall efficiency of the Continuous Commissioning® (CC®) process relies on the interactions of the commissioning team, the building owner, and the building operators. At times the process may be hindered by the traditional "open loop" approach of planning, implementing, and presenting commissioning measures, then waiting for results based on analysis and availability of whole-building utility data. One way of closing this loop and providing instantaneous feedback to all parties is through "micro" level data analysis to evaluate individual measures. This paper presents a case study of a CC® project at Anderson High School in Austin, Texas. Measures for optimizing air and hydronic systems were implemented. Concurrently, building automation system trend data relevant to each measure were analyzed. Results of this analysis helped to improve response times for the commissioning team, reassure savings potential for the building owner, and instill confidence in proper equipment function for the building operators. These effects all in turn improved the CC® process efficiency, which was validated by the whole-building savings results following completion. Through six months, post-CC® utility bills show an estimated utility savings of $39,192 without sacrificing comfort, already exceeding pre-assessment projections for the entire year.

Keywords:
Building Automation System, Commissioning, Measurement, Utility Analysis Verification,

1. Introduction

As energy prices continue to rise in today's economy, utility costs are becoming an increasingly critical part of institutional budgets. As the budgets themselves are staying relatively stagnant, these costs cut into Operation and Maintenance (O&M) funds that could be used for equipment retrofits, further compounding the issue. Continuous Commissioning® can offer a solution to this problem, with typically faster payback than capital retrofit while also addressing existing O&M and comfort issues. The CC® process works within existing HVAC systems to continuously optimize operation, comfort, and energy use given the *current*, and not original design conditions (Verdict et al., 2004). It can also serve as a tool for achieving sustainability and emissions goals. The value of CC® to the client can be further improved when the efficiency of the process itself is optimized.

Continuous Commissioning® was developed by the Energy Systems Laboratory (ESL), and traditionally consists of sequential steps such as conducting system measurements, developing a CC® plan, implementing CC® measures, and documenting energy savings and comfort improvements (Claridge et al., 2002). All of these steps involve interactions with building owners and operators to help identify problem areas, gain approval for proposed measures, and report results to validate the project. The efficiency of these interactions are crucial to the success of the project. Just as in control theory, introducing measured feedback throughout the CC® process can enhance its efficiency and its ultimate deliverables.

2. Closing the CC® process loop

The primary "output" of the CC® process used to measure its success – and potentially to feed back to improve the process – is energy savings. The least expensive method of CC® project savings measurement is using building utility data gathered over several months before and after implementation, as outlined in the International Performance Measurement and Verification Protocol (IPMVP) Option C (EVO, 2012). This may not, however, be the most effective method as its lengthy delay renders it essentially an open-loop approach. Accurate analysis with this approach can take up to 12 months or more of data (Sellers, 2001), long after quantifiable results are demanded by the owner, and too late for corrective action by the engineer. Moreover, whole building utility data encompasses interactions between all building equipment, and fails to demonstrate the success of individual measures as they are implemented. Using trend data within the Building Automation System (BAS) can be a cost effective way to improve the frequency and resolution of this feedback and close the process loop.

During the planning and implementation phase, baseline time series trend data can identify operational issues. Ideally, automated "dashboards" can monitor trends and notify operators when certain limits are exceeded (Seidl 2006). Such tools are currently in development by ESL and others. In addition to real-time troubleshooting, trends showing the success of "trial" measures can be useful to ease concerns of building operators over proposed sequence modifications. In the post-implementation phase, gathered data can be filtered to verify the functionality and efficiency of implemented measures. This information can be used by the CC® team to iterate the implementation phase as necessary and fine-tune CC® measures, as well as to give an early savings projection to building owners and justify the project sooner.

CC® was recently performed at Anderson High School in Austin, Texas by Texas Energy Engineering Services, Inc. (TEESI).ESL provided whole building M&V services following project conclusion. Throughout the project, TEESI engineers used the closed-loop approach and BAS trend data as described above to successfully improve the process efficiency and ultimately the end product.

3. Facility Description

Anderson HS has a total square footage of 265,180 ft^2 and is located in Northwest Austin, Texas. The school was originally constructed in 1973 with multiple renovations since that time. In particular, a new band hall and science building were added in 2009 with a separate satellite central plant.

The main central plant at Anderson consists of two water-cooled centrifugal chillers totaling 600 tons with primary-secondary variable speed pumping. Four hot water boilers totaling 8,000 MBH in capacity also serve the main building. The satellite central plant for the science and band addition consists of a 120 ton air-cooled chiller and two hot water boilers totaling 2,700 MBH in capacity.

On the air-side, most classroom areas at Anderson are served by variable volume Multizone (MZ) Air-Handling Units (AHUs). Single Zone (SZ) variable volume AHUs serve large areas such as the cafeteria and gymnasium. Finally, the new band and science hall are primarily served by Single Duct Variable Air Volume (SDVAV) units with terminal hot water reheat.

4. Pre-CC® Control

Prior to implementation, occupants could control space cooling setpoints between 67°F and 77°F. The majority of spaces were set at the lower end of this range. Heating/cooling deadbands were only 2°F if they existed at all. In the case of the classroom MZ units, no deadband was in effect. Zone mixing dampers were controlled to a single setpoint. On the MZ air-handlers themselves, Cold Deck (CD) setpoint was a constant 55°F, and both Hot Deck (HD) setpoint and VFD speed were reset based on outside air temperature alone. Although space temperatures could still be controlled with the zone dampers, this was often accomplished wastefully by mixing heated and cooled air to deliver ultimately neutral air to already-satisfied spaces. Moreover, although variable volume, the open loop nature of fan speed control led to minimum VFD speed being 70% of design in order to assure proper airflow in heating.

On SZ units, although Supply Air Temperature (SAT) and VFD speed were controlled based on space temperature feedback, both were controlled simultaneously. This created potential for overly high flows of neutral air, costing fan energy, as well as significant overshoot and hunting of space temperature.

SDVAV units at Anderson controlled fan speed based on maintaining a constant static pressure setpoint. These units are also equipped with pressure independent outside air control, which before CC® was set to deliver a constant volume of outside air.

On the water-side, secondary Chilled Water (CHW) pump speed was controlled to a constant "worst case scenario" Differential Pressure (DP) setpoint. Hot Water (HW) pumps were constant speed and were found by the CC® team to be in "Hand" position and running around the clock even with the boilers disabled.

In addition to control issues, TEESI also identified HVAC equipment and sensors that required repair or upgrade. All of these issues and more were addressed in the implementation phase with the aid of consistent micro level trend data analysis and feedback.

5. Implementation Phase and Micro Level Feedback

As part of the CC® planning process, BAS points relevant to the most significant measures were trended using the controls frontend. From this data, a baseline was established to use for feedback during implementation. To properly execute a closed-loop CC® approach, careful planning of BAS trends is critical. Ideally, trending every system point would ensure baseline data were available for areas found to be of interest following implementation. In reality, trending capabilities are limited by the time needed to set them up, the effort needed to filter results, and the network traffic created when downloading data to workstations. As such, a certain amount of foresight is necessary to predict "heavy hitting" measures and their related BAS points prior to implementation.

After the planning and setup phase, the proposed measures were approved by the school district and implemented in the BAS. Implementation began with simple changes such as space setpoint limitations (72°F minimum in cooling) and widening deadbands to meet or exceed current energy code requirements. Operating schedules were also trimmed to reflect actual occupied hours. Next, modifications to actual unit control sequences were made by TEESI engineers. Finally, repairs were made to the outside air humidity sensor and Gym unit CO_2 sensor, and the hot water pumps (two in total) were retrofitted with Variable Frequency Drives (VFDs). The following sections describe the implemented control sequences and micro data analysis.

5.1. Multizone AHUs

Cooling/Heating demand based reset strategies have been shown to yield significant energy savings over those based purely off outside air temperature (Texas A&M, 2008). Ideally, the two should be combined so as to prevent "rogue zones" from ramping up the system unnecessarily (Wei et al., 2004). However, it should first be verified these zones do not have high internal loads that legitimately require more cooling. If well monitored, combined zone-demand and outside air based control can help to identify zones with relatively high internal heat gain so that other action may be taken. This combination control was implemented widely at Anderson HS, starting with MZ AHU fan speeds being reset to maintain the most open zone damper position (critical cooling zone) at 90%.

As discussed, the pre-CC® MZ units were without heating/cooling deadbands because zone dampers controlled to a single setpoint. During CC®, an *effective* deadband was implemented by sequencing units to take no heating action until any zone actually needed heating (space temperature below separate heating setpoint). Rather than controlling off of outside air temperature, HD temperature and heating fan speed were reset to maintain all zones above their respective heating setpoints. This also had the effect of allowing for a lower minimum fan speed, since speed could be increased as necessary should any zone require heating. The existing resets based on outside air were used as upper limits.

Following implementation, trend data were downloaded and filtered to ignore unoccupied periods. Because fan laws relate fan power to the speed cubed, the root-mean-cube VFD speed was calculated for each day and plotted against the corresponding daily average outside air temperature. Figure 1 shows the results of this analysis. The data confirmed that the new sequence was working properly and saving energy while in general improving comfort.

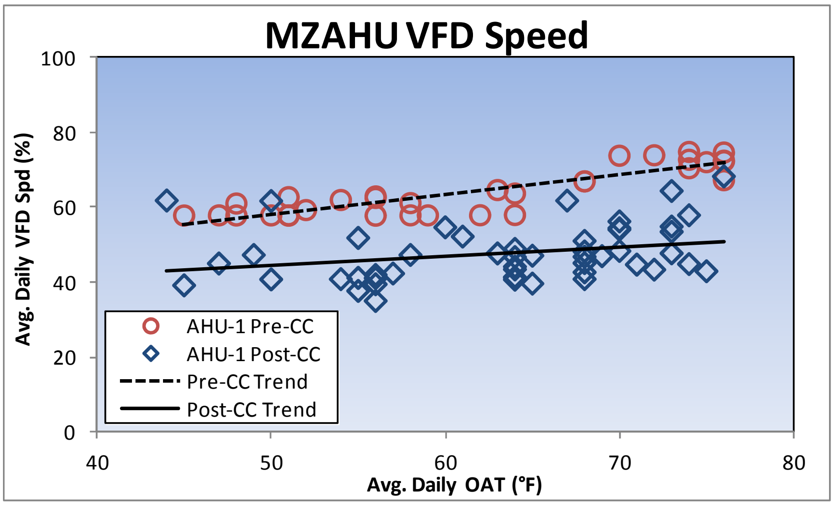

Figure 1. Multizone AHU fan speed trend pre and post CC.

5.2. Single Zone AHUs

The existing SZ AHU sequences at Anderson were already using a demand based reset of SAT and fan speed, but not to optimal capacity. Both supply temperature and air flow were reset at the same time in response to space temperature, causing issues for both energy consumption and occupant comfort. During CC, the sequence was modified to split the sensor signal and respond to cooling or heating demand with warmer or colder air, respectively, first before ramping up fan speed. The fan speed was allowed to modulate from its minimum setting only once SAT reached its lower or upper limit. Figure 2 shows normalized fan speed trend data. The data once again confirmed to the CC® team that the sequence modification had the desired effect

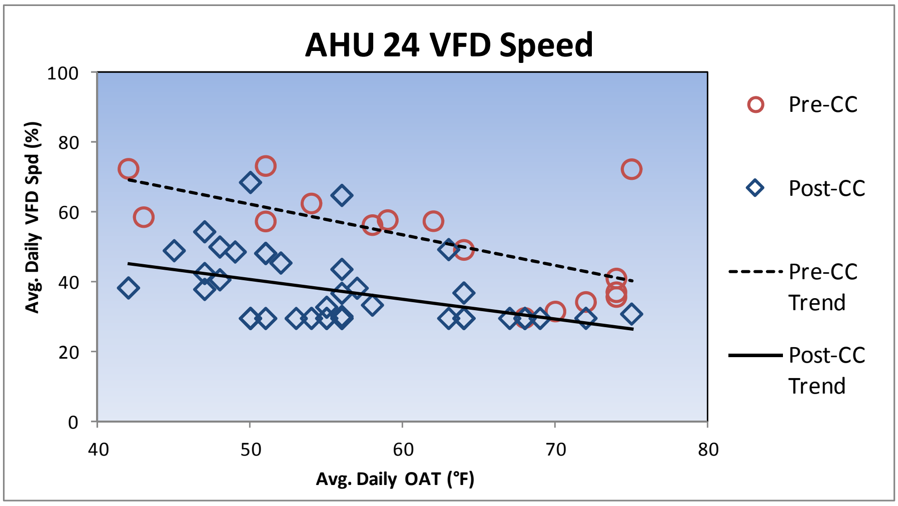

Figure 2. Single Zone AHU fan speed trend pre and post CC.

The existing simultaneous control of supply temperature and flow also caused the units to overreact to space cooling or heating demand and overshoot the setpoint. This resulted in large, potentially uncomfortable temperature oscillations in the space. The oscillatory behavior was identified from time series trend data directly within the BAS and remedied immediately with the new sequence. Splitting the thermostat signal had the secondary effect of softening the AHU response to space temperature, thus tuning and tightening the control. Figure 3 shows the pre-CC® issue observed from trend data and the subsequent correction resulting from the modified sequence.

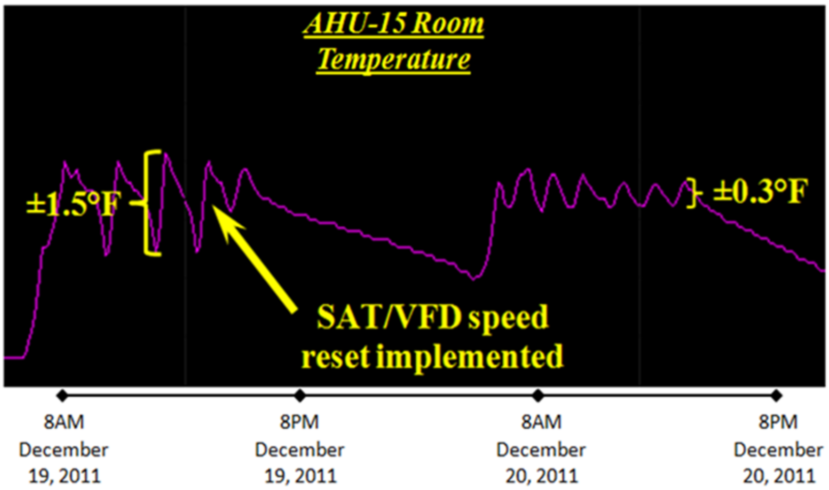

Figure 3. Single Zone AHU space temperature oscillations corrected during CC.

5.3. SDVAV Units

Implementation on SDVAV units provided examples of using micro level trends analysis and feedback to enhance other areas of CC® in addition to savings results. Like MZ and SZ AHUs, it was recommended that the SDVAV units use a demand-based reset, in this case for static pressure setpoint (reset to maintain most open terminal unit damper at 90%) rather than keeping it constant. This was met with some skepticism from building operators worried about undercooling and increasing hot calls. It was agreed that the proposed sequence be implemented on a trial basis and monitored by the CC® team. Figure 4 shows the results of this trial; the most open damper was successfully maintained at 90%. Being pressure independent boxes, the system still necessarily receives the exact same amount of cooling as before CC® – only at a more efficient system pressure – provided all dampers are less than full open. Figure 4 also depicts the most open damper position on a typical pre-CC® day, when the constant static setpoint was too high and forcing all zones to throttle airflow needlessly. The resultant decrease in fan speed after implementation is also shown, along with the outside temperature profiles on both days for comparison. After presenting the trial results to the District, the reset was approved and implemented for all SDVAV units. Figure 5 shows the weather-normalized fan speed data confirming long-term savings in addition to functionality.

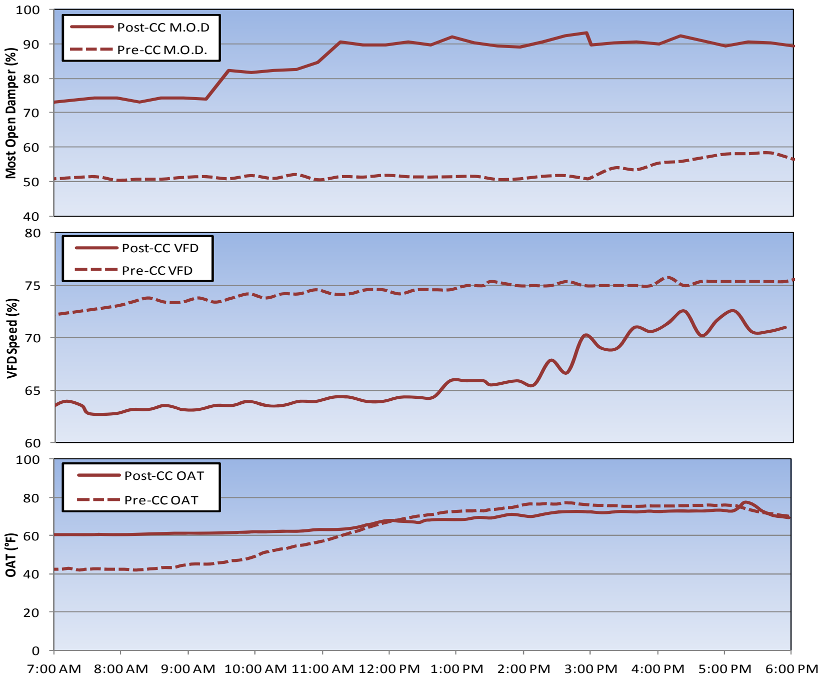

Figure 4. SDVAV static pressure reset trial results.

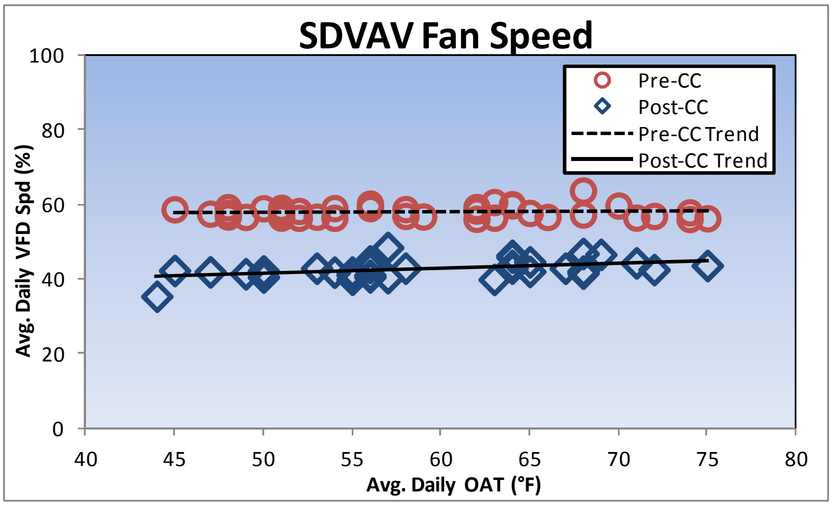

Figure 5. SDVAV fan speed trend pre and post CC.

A demand based reset was also proposed and tested for SDVAV SAT. In this case, trend analysis identified short-cycling in the satellite chiller. This was attributed primarily to the chiller being oversized for the present load, i.e. already occurring before CC®. Nevertheless, corrective action was taken by the CC® team as a result of the discovery. The District was notified and the reset was removed to avoid complicating the issue.

SDVAV-served spaces at Anderson HS are equipped with motion sensors whose signals are tied into the BAS. The system was previously using these signals to set back or set up the space temperature setpoint when no occupancy was sensed. Building on this, and extending the concept of demand based resets, the CC® team implemented a reset of the outside air volume setpoint based on the number of occupied zones. A sequence was written to poll all motion sensor signals and decrease the setpoint as necessary assuming zones with no motion were completely unoccupied. Following implementation, pre and post CC® trended outside air CFM measurements were filtered for hours of operation only and sorted into hourly time bins. The average for each bin was computed and plotted in Figure 6. It was discovered that some occupant diversity was always present, that is, at least one zone was almost always unoccupied. As expected, significant ventilation setback was possible during shoulder periods before and after school, without violating ventilation codes.

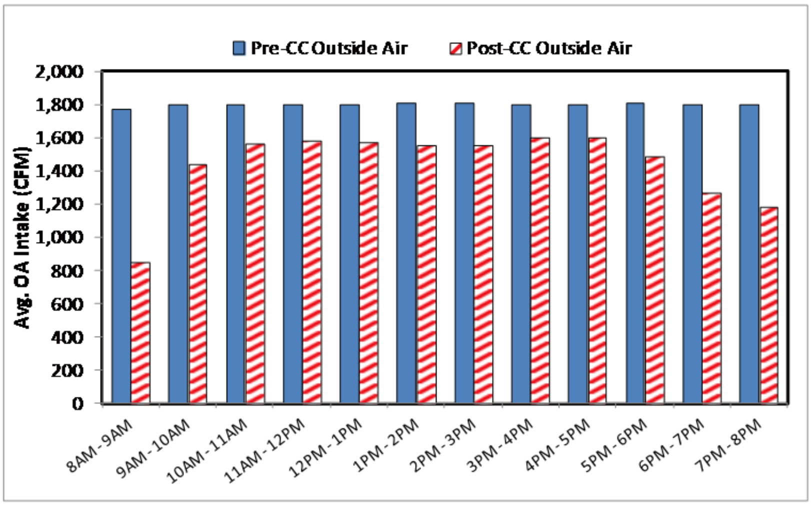

Figure 6. Outside air intake time bin analysis.

5.4. HW Plant

Control of Anderson's boilers within the BAS was limited to enable/disable functionality only, and thus fell outside the scope of the project. However, as mentioned, it was discovered the HW pumps were running around the clock. This issue was remedied in the field and the pump statuses continued to be monitored by the CC® team in the BAS. The data were again sorted in to time bins and the fraction-of-time-found-running in each bin was calculated for both pumps. Figure 7 shows the results of this analysis. After automatic control was restored, after-hours operation was limited to night setback calls only, and the pumps staged as intended with HWP2 rarely coming on.

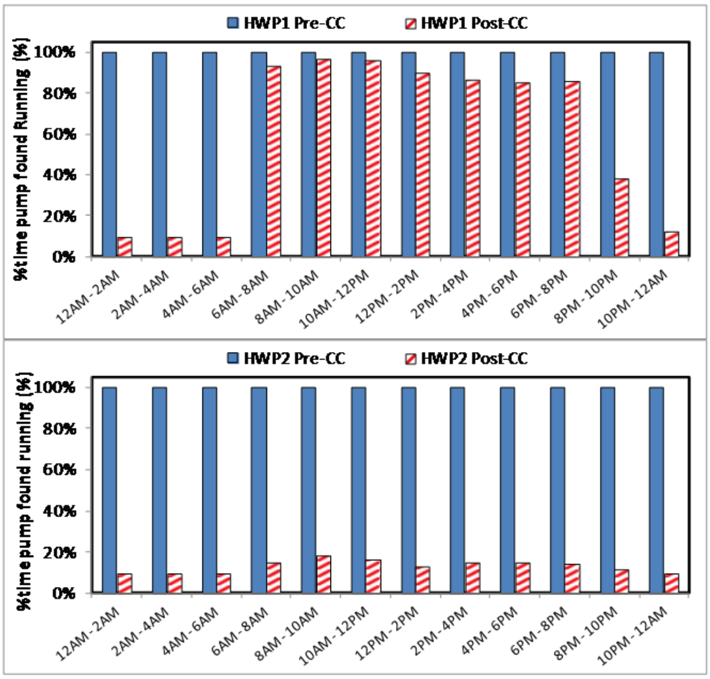

Figure 7. HW pump run-time analysis.

5.5. CHW Plant

As with the HW boiler control, setpoint reset functionality was limited within the BAS. Thus, no direct changes to the chiller sequence was made. However, the cooling supplied to the building was trended in the BAS to monitor the indirect effects of changing setpoints, widening deadbands, reducing reheat, etc. Figure 8 shows the average daily loads during operation plotted against corresponding average daily outside air temperatures. Sequence changes related to CHW load were successful in reducing the CHW consumption as expected.

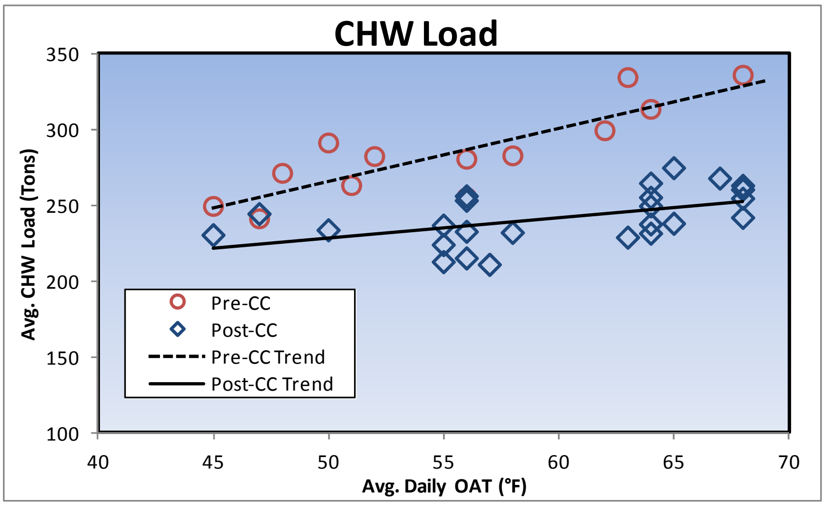

Figure 8. CHW tonnage trend pre and post CC.

A demand based reset scheme was also applied to the CHW secondary pumping system. The DP setpoint for the secondary CHW pump VFDs was reset in order to maintain the most open

AHU CHW coil valve at 90%. Pump speed trend data were analyzed and plotted in Figure 9. It was suspected prior to implementation that the existing constant DP setpoint was far higher than necessary under most conditions. Post implementation trend data confirmed this suspicion. Resetting based on actual demand made the system more dynamic and self balancing, allowing the pumps to slow significantly.

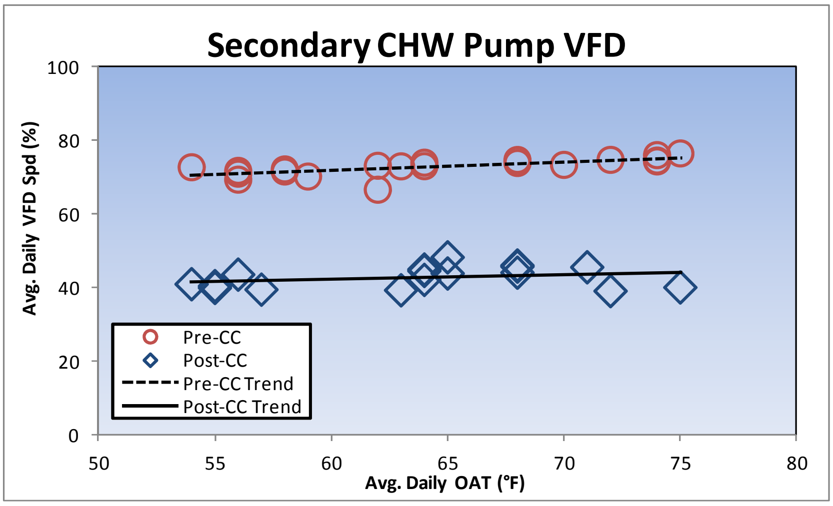

Figure 9. Secondary pump speed trend pre and post CC.

6. Savings Summary

The preceding sections demonstrate the value of analyzing trend data *during* the CC® process to assess individual measures and fine tune or take corrective action where necessary. The information can also be used following implementation to form an early savings projection for each measure and for the entire project, long before a meaningful result is available from monthly utility data. At Anderson HS, basic assumptions of efficiencies and baseline equipment equivalent-full-load-hours were combined with the compiled trend data to yield early savings projections. These projections were compared with savings estimates from the assessment phase before CC® used to secure funding. It is interesting to note that pre-CC® predicted savings resulting from reduced equipment runtime were overestimated in most cases, while savings calculations involving demand based resets and sequence modification were overly conservative. In this way, information gained from micro-level analysis is also useful for reviewing pre-project assumptions and advising future projects in the proposal/funding stage.

From the early micro-level analysis, TEESI projected savings of approximately 18% over the base year. Macro-level M&V provided by ESL, through six months following implementation, validates and even exceeds this projection, showing 21% electricity savings with an additional 17% natural gas savings over the base year. This corresponds to $39,192 in total utility cost savings thus far using prevailing rates, already surpassing total first year pre-project projections. Figure 10 shows the cumulative cost savings during the post CC® period (Courtesy ESL).

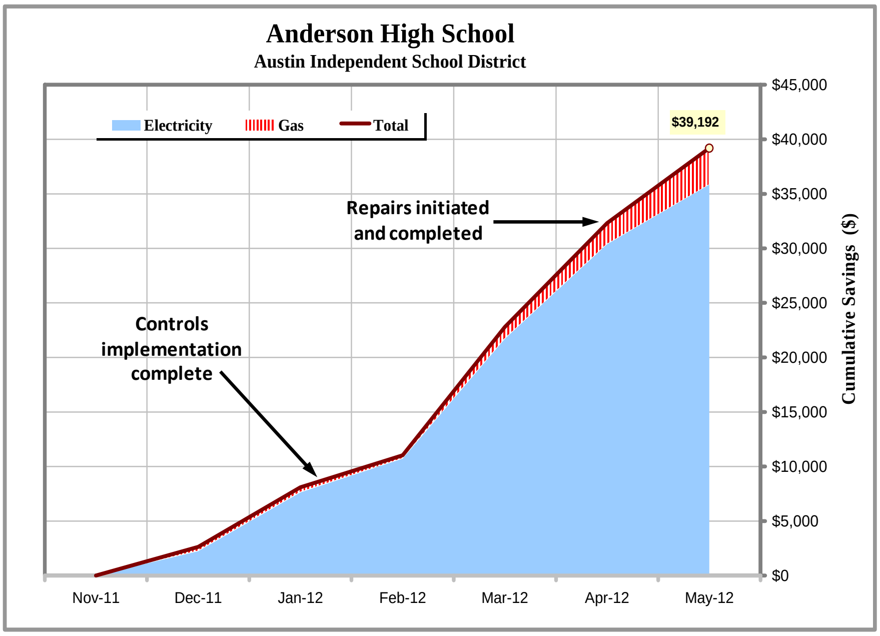

Figure 10. Cumulative cost savings December 2011 through May 2012.

7. Conclusion

Continuous Commissioning® is a process intended to improve the efficiency of a building, but the efficiency of the process itself can be improved as well. CC® at Anderson High School in Austin, Texas has saved the school district nearly $40,000 in just six months since implementation began. This success was due in part to team efforts to enhance the CC® process through analysis of trend data relevant to individual measures. These data were critical for quality control of sequence modifications, supporting evidence for measure approval, and early justification of the project. They may also prove useful in fine tuning assessment-phase savings estimates for future projects.

Using "micro" level data analysis and feedback throughout the CC® process, in concert with "macro" level whole building M&V down the line, can be a valuable tool. Automated tools such as dashboards are being developed to help streamline this process. However, for best results, they should be used as a supplement to – and not replacement for – sound engineering practice and experienced hands-on analysis. In addition to potentially increasing project savings, micro analysis can also increase building owner and operator confidence in the CC® team and process. This confidence helps beget more cooperation and success in future projects, a snowball effect that ultimately maximizes savings and reduces the strain on institutions' ever tightening budgets.

Acknowledgements:

The authors would like to express appreciation for the assistance provided by the Austin Independent School District (AISD) facility department, maintenance staff and Anderson High School staff. We would also like to thank, in particular, Farshad Shahsavary, Ken Rehberger, Jim Dillard, Stuart Miller and Jess Williams for their time and assistance throughout the project. Our complements go to AISD top management for their foresight in undertaking this project. Finally, thanks to the Energy Systems Lab for whole-building savings figures and input during the commissioning process.

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Optimising the Low Temperature Cooling Energy Supply: Experimental Performance of an Absorption Chiller, a Compression Refrigeration Machine and Direct Cooling – a Comparison

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Abstract:
A strategy to optimise the low temperature cooling energy supply of a newly build office building is discussed against the background of a changing energy system. It is focused on, what production way - Direct Cooling, the Compression Refrigeration Machine or the Absorption Chiller provided with heat from Combined Heat and Power Plants - has the lowest primary energy consumption at what load level. For low levels this is direct cooling. If demand exceeds the capacity of direct cooling, the absorption chiller is the option to choose. However, in future the compression refrigeration machine is more efficient at providing high load levels than the Absorption Chiller. The operation analysis shows that flow rates are often held constant and the re-cooling temperatures are often above the ambient temperature. By the integration of automatic flow rate control and lowering the re-cooling temperature of the chillers, electricity consumption of pumps can be reduced and energy efficiency enhanced.

Keywords:
Compression refrigeration chiller, direct cooling, primary energy optimisation, trigeneration

1. Introduction

In order to reduce the energy demand of a newly built office building 50% below the official requirements the buildings envelope was optimised. Therefore heating demand in winter and cooling demand in summer is decreased. Furthermore, it has a multivalent energy system with high and low temperature heat as well as cooling energy supply and the possibility to supply heat to existing buildings at the company's campus.

Recent results of the energy monitoring of this building show that low temperature cooling demand is at almost all times below 700kW and at most times below 100kW. At the same time there is a total installed capacity of about 1700kW for providing it.

Therefore this paper discusses the process of optimising the low temperature energy supply. The question in focus is what chiller needs the minimum of primary energy at what operating state. Furthermore it is analysed what circumstances must be given that the results hold true.

2. The Low Temperature Cooling Energy System

Figure 1 shows the three ways low temperature cooling energy can be provided in the building. The low temperature energy system is designed to provide cooling water at a temperature of 8°C and a spread of 6°C. So far the operation of the components is bound to fixed levels of ambient temperature:

Direct Cooling (DC): Three re-cooling plants each with a capacity of 800 kW are installed on the roof of the building. For DC a capacity of 350kW can be used. So far DC is planned to be operated if the ambient temperature is below 10°C.

Compression Refrigeration Machine (CRM): The CRM has a capacity of 665kW. It is re-cooled by the re-cooling plant on the roof. The temperature of the re-cooling water is planned to be 27°C with a spread of 6°C. So far it is planned to be operated, if the ambient temperature is above 10°C and below 30°C.

Absorption Chiller (AC): The AC has capacity of 710kW. The high temperature heat buffer storage provides it with heat. The inlet temperature level at the AC is planned to be 95°C with a spread of 15°C. The buffer storage is served by the two on-site combined heat and power plants (CHPs). It is re-cooled in the same way like the CRM. So far the AC is planned to be operated if the ambient temperature is above 30°C.

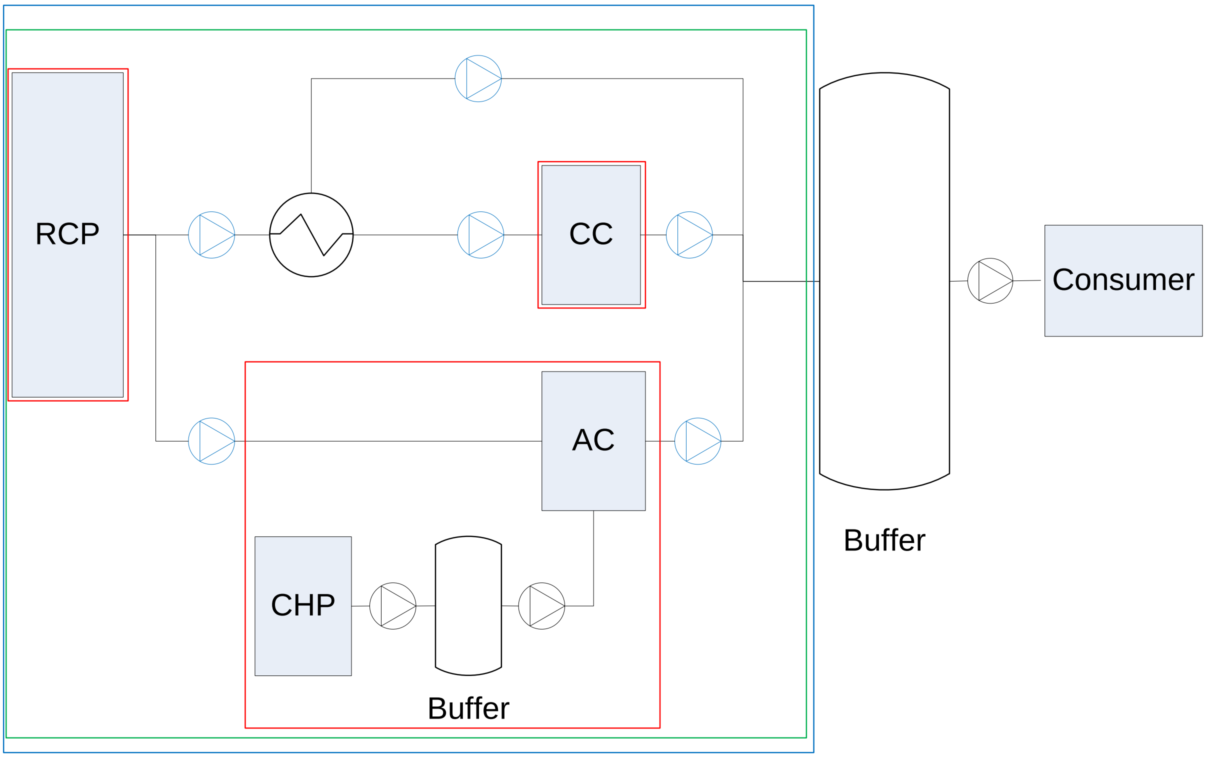

Figure 1: Low Temperature Cooling Energy System

For decoupling production time and usage as well as serving peak loads, the produced cooling energy is stored into a buffer storage. It has a capacity of 8000 litres. In total the buffer storage has a connected load of 720kW. The cooling cycle is planned to be operated at 9°C. Therefore it has a planned storage capacity of around 9kWh.

All pumps of the system in focus have a frequency converter either internally or externally. Therefore their operation can be flexible. However, not for all of them automatic control is implemented. The re-cooling and cooling water pump of the AC and the CRM as well as the pumps of the re-cooling plant connecting to DC and the CRM are controlled manually. Most of the time, they have a set-point of 100%.

3. Methodology

3.1. General Approach

This paper aims at optimising the primary low temperature energy supply. Therefore the primary energy factor (PEF) of one unit of low temperature cooling energy supply to the buffer storage is chosen to be the dependent variable to optimise.

All the components left of the low temperature storage buffer as depicted in Figure 1 are included into the calculation of the PEF of low temperature cooling energy. The PEFs will be classified in accordance with the load of the considered cooling machines. As a consequence operators will know at what demand what machine is the most efficient.

The PEF is calculated for different energy balance levels in order to show the impact of the different components of the system. The levels chosen are depicted in Figure 1: At first the red framed chillers themselves are looked at. Then the balance is extended to the heat sinks. This is the green framed area without the blue marked pumps. These are finally integrated into the calculations. During further analysis this last level will be referred to as the total PEF.

Single components have not been optimised so far. Based on the impact analysis it can be estimated where optimisation is most effective if any potential can be uncovered. The single component analysis and the analysis of their interaction will check for options of operating enhancement. Furthermore they will show at what operating parameters the results for the total PEF hold true.

3.2. Primary Energy Factors

In order to calculate the primary energy factor for each way of the cooling energy supply the factors for the single energy flows of each part of the system need to be determined. There are two forms of energy flows supplied to the chillers: Heat and electricity. Furthermore electricity is provided by the public grid and by cogeneration.

The primary energy factor of electricity from the public grid is chosen in accordance with the German standard on calculating the primary energy demand for buildings, the DIN EN 18599. At present it is 2.6 and represents the factor of the German annual average electricity mix of the public grid.

The combined heat and power plants are gas-fired. The primary energy factor for natural gas is 1.1. However, there are several methods for the allocation of a CHP’s fuel to its products and therefore for gaining the primary energy factor of heat and electricity of cogeneration. A detailed description of these methods can be found in Mauch et al (2010) and Verein Deutscher Ingenieure (2008).

Here the Electricity Credit Method is chosen for further analysis. This is as well in accordance with the DIN EN 18599. Therefore the PEF of heat is calculated as follows:

$$PEF_{Heat} = \frac{\dot{Q}_{Gas} \cdot PEF_{Gas} - \dot{Q}_{Elec} \cdot PEF_{Elec}}{\dot{Q}_{Heat}}$$

Here Q_{Gas} is the energy flow contained in the CHPs' gas input, Q_{Elec} and Q_{Heat} is the energy flow contained in the produced electricity and heat of the CHPs. The PEF_{elc} is the PEF of the electricity that is displaced through the CHPs' production. As there is no other internal electricity production this is the electricity of the public grid.

This method pays respect to the project's economical and technical circumstances as well as allows the evaluation of the technologies against the background of the ongoing energy economic development: Economic feasibility of the CHPs is only given if capacity utilisation is high. During summertime this was planned to be ensured by providing production lines in existing buildings on the campus but primarily the absorption chiller with heat. Therefore the absorption chiller justifies the installation of the CHPs - with heat as their main product and electricity as their by-product. However, the latter can be produced all day round. Therefore electricity is assumed to displace electricity of the base load mix. Base load, consisting mainly of nuclear power and coal has a primary energy factor of 2.9 according to Gemis 4.7 (Institute for Applied Ecology, 2011). As the public energy system changes and politics is increasingly heading towards a sustainable energy system with a large share of renewable energy and the dismantling of the load system, efficiency of the sole system gains importance. In order to estimate the validity of the results against this background the PEF is calculated with a PEF of one.

As cogeneration is only part of the building's energy system due to the AC the electricity used by the CRM and DC is evaluated by the primary energy factor of the public grid. The electricity caused by the AC is evaluated with the PEF of the assumed displacement electricity mix.

3.3. Integrating the Buffer Storage

There is one buffer storage in the system under consideration. It acts as a hydraulic separator evoking a time base shift: The heat the CHPs produce is not simultaneously used in the AC. Instead it is stored in the buffer storage. Consequently, the allocation of production and losses to one unit of cooling energy supply is not precise. The underlying problem is the determination of storage efficiency at a certain point in time.

Here storage efficiency is determined by the sum of energy leaving the buffer during ten load cycles and the sum of energy entering the buffer storage during this time. One load cycle is defined as the interval from starting to charge the buffer storage to the next time the buffer storage is about to be charged.

During one load cycle often more energy is discharged than charged. Therefore choosing one load cycle is not enough to map reality. Ten load cycles are chosen for approximation.

3.4. Data Selection and Preparation

The most recent data for one year is chosen. This is data from 1/8/2011 to 1/8/2012. In order to perform the analysis in a consistent and efficient way the incoming data is processed using the software DataStorage.

Calculations are based on meter data that comprise mistakes: Some values are not valid, as they do not fulfill the criterion of monotony. Therefore these values are masked out. Assuming that counters count correctly missing values are calculated by interpolation.

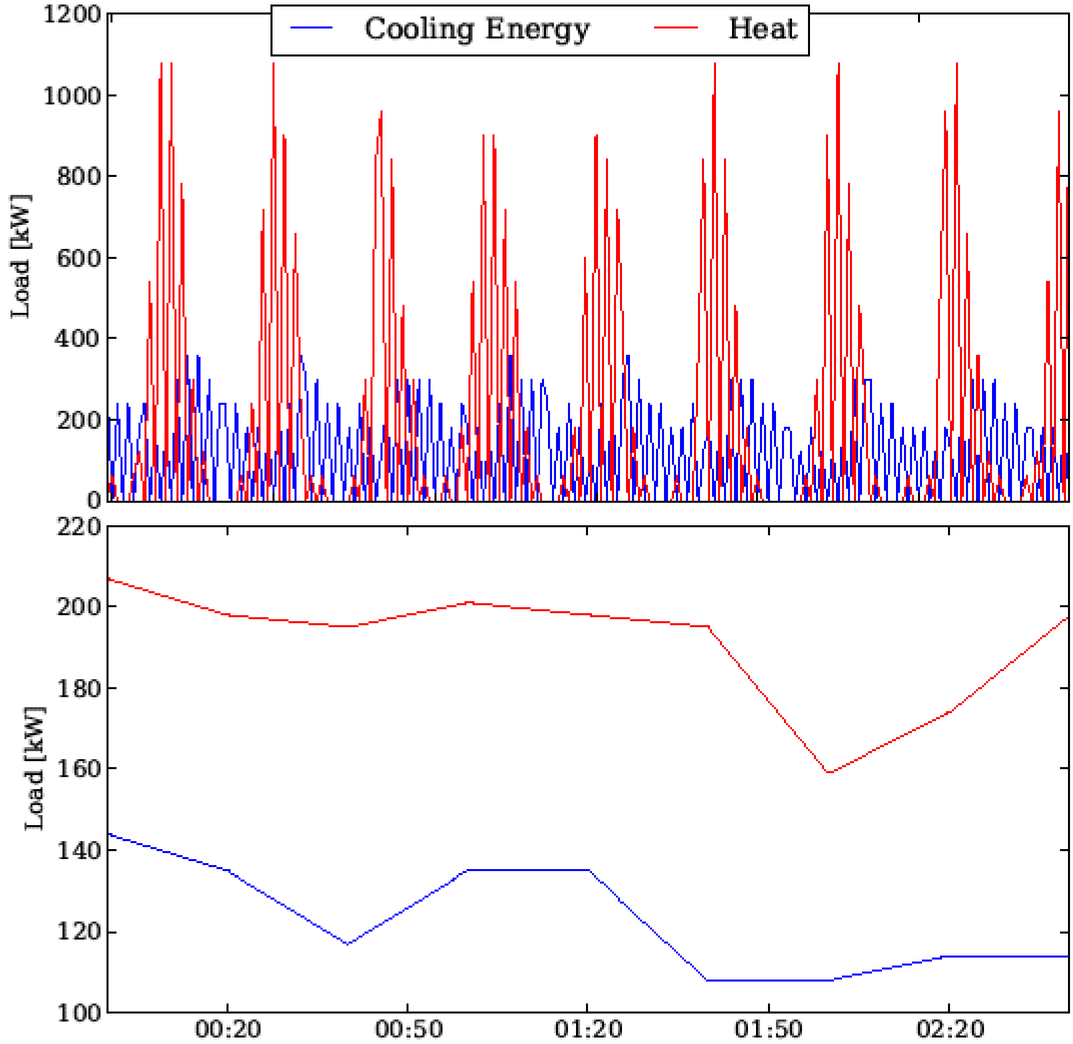

Figure 2: Choosing a Time Interval for the Analysis

Based on the result data calculation has been made. Figure 2 shows the obstacles to be tackled during this process:

- Data is collected every minute from the building control system. However, the buildings control systems receives data from the sensors at different and time-dependent intervals. Therefore data does not fit together at all times at this resolution. In Figure 2 this can be monitored in the upper graph. This is the derivation of the course of the counter values and every second value is zero. At the same time the machine is running. Therefore this shows that the data of this sensor has not been queried during the course of the minute. Comparing the course of data for heat and for cooling energy, these zero values can be observed at different points in time.

- Due to the systems inertia the output caused by a special input does not exit a component of the system at the same time as it enters the component. Furthermore a component sometimes operates at no quasi-static state. Figure 2 shows this for the AC. Although the machine is running for hours there are alternating peaks of heat and cooling energy. However, the production of the cooling energy is caused by the machine's heat input.

The analysis for optimising operation requires an analysis in accordance with the rules of a valid energy balance. Against the background of the above described obstacles, the underlying time interval of the analysis should be chosen that wide that this requirement is fulfilled. However, increasing width of the time intervals lead to a decreasing density of the results at high load levels and a high density of results is needed for all load levels of a component for optimising operation. Consequently, there is a conflict of sticking to the rules of making a correct energy balance and obtaining a significant result for the optimisation process. This is solved by choosing an interval of 20-minute average values. Single values still do not fulfill the requirements for the energy balance over one component and are taken out of the results.

3.5. Further assumptions

The energy consumption of pumps is so far not based on continuous measurements. However, temporary measurements have been undertaken for some of them at characteristic operating states. Here electricity consumption has been logged. For others the electricity consumption at the design point is assumed. Table 1 gives an overview of the assumed electricity consumption of the pumps.

Table 1: Assumptions for the Electricity Consumption of the Pumps

Pump	*Electricity [kW]*	*Quality of assumption*
Re-cooling water pump AC	*18.0*	*Measured*
Re-cooling water pump CRM/DC	*13.0*	*Design point*
Re-cooling water pump CRM	*3.1*	*Measured*
Cooling water pump AC	*2.2*	*Design point*
Cooling water pump CRM	*2.2*	*Design point*
Cooling water pump of DC	*1.6*	*Design point*

4. Results

4.1. Primary Energy Factor at the Status Quo

Figure 3 shows the results for the PEF of the different chillers for each of their load states and at the different energy balance levels as defined in Chapter 3.1. The results for the total PEF show, that DC has the lowest PEF at most times. If cooling demand cannot be provided by DC, operating the AC is the option to choose. In general the primary energy efficiency rises with increasing load level.

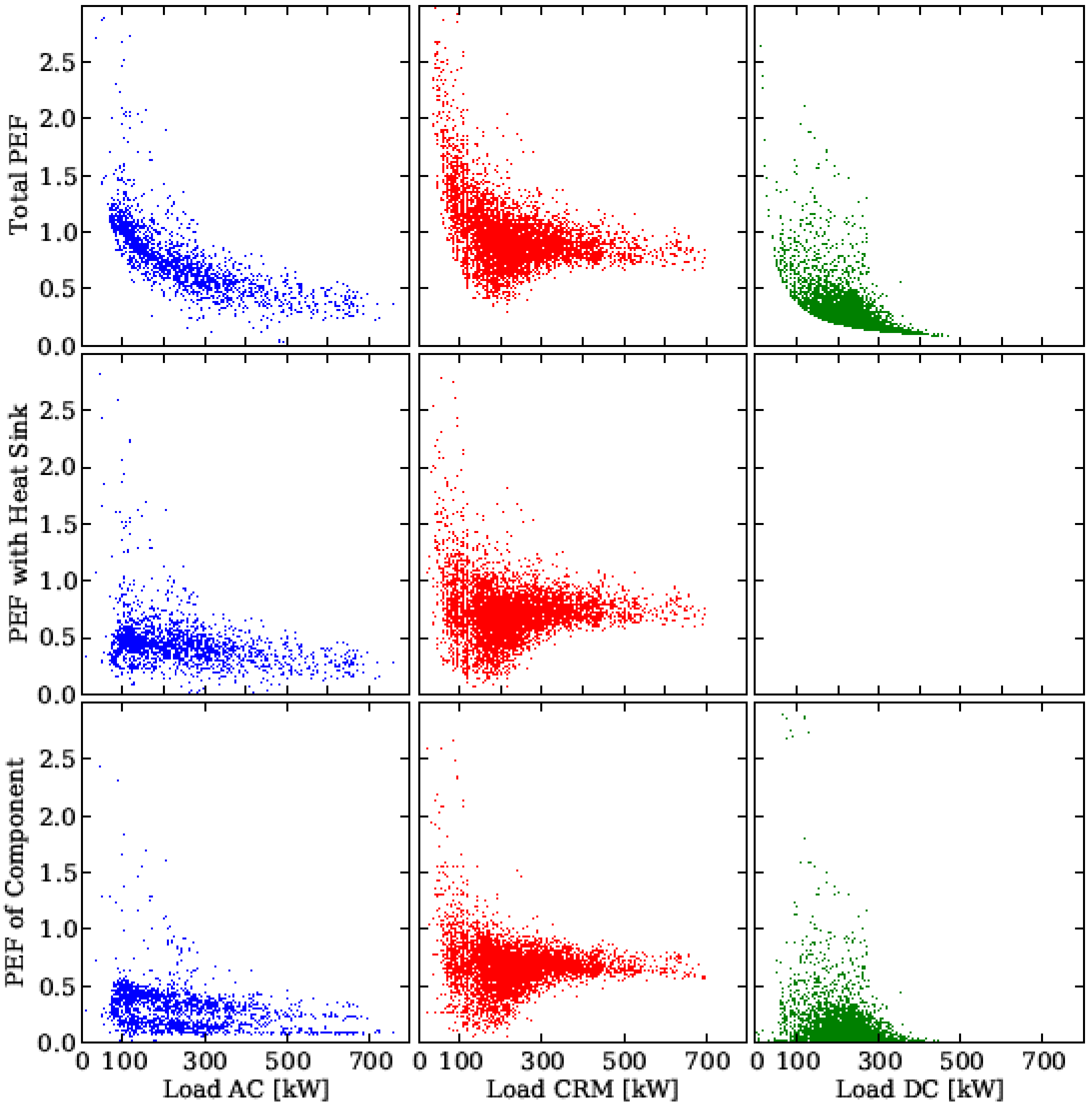

Figure 3: Calculated Present Primary Energy Factors of the Absorption Chiller (AC), the Compression Refrigeration Machine (CRM) and Direct Cooling (DC) at Different Load Levels based on Measured Data

The results of the sole component of the AC are for high load levels lower than for the CRM. In the load range from 100 to 200kW they are partly level-off. The energy efficiency of the AC is only 0.7 compared to the one of the CRM with 4. However, the heat of the CHPs has only an average PEF of 0.17, whereas the PEF of the electricity of the public grid for the CRM is 2.6.

The integration of the heat sink - the re-cooling plant - into the considerations increases the PEF only slightly, as the average efficiency of the re-cooling plant is 18. The re-cooling plant impacts the results for the AC more than those for the CRM. This is due to the fact that the re-cooling plant has with 20 during the operating time of the AC a lower average energy efficiency than during the operating time of the CRM with an average efficiency of 26. Furthermore the electricity consumption caused by the AC is evaluated with a PEF of 2.9, whereas the electricity consumption caused by the CRM is evaluated with a PEF of 2.6 (cp. Chapter 3.2).

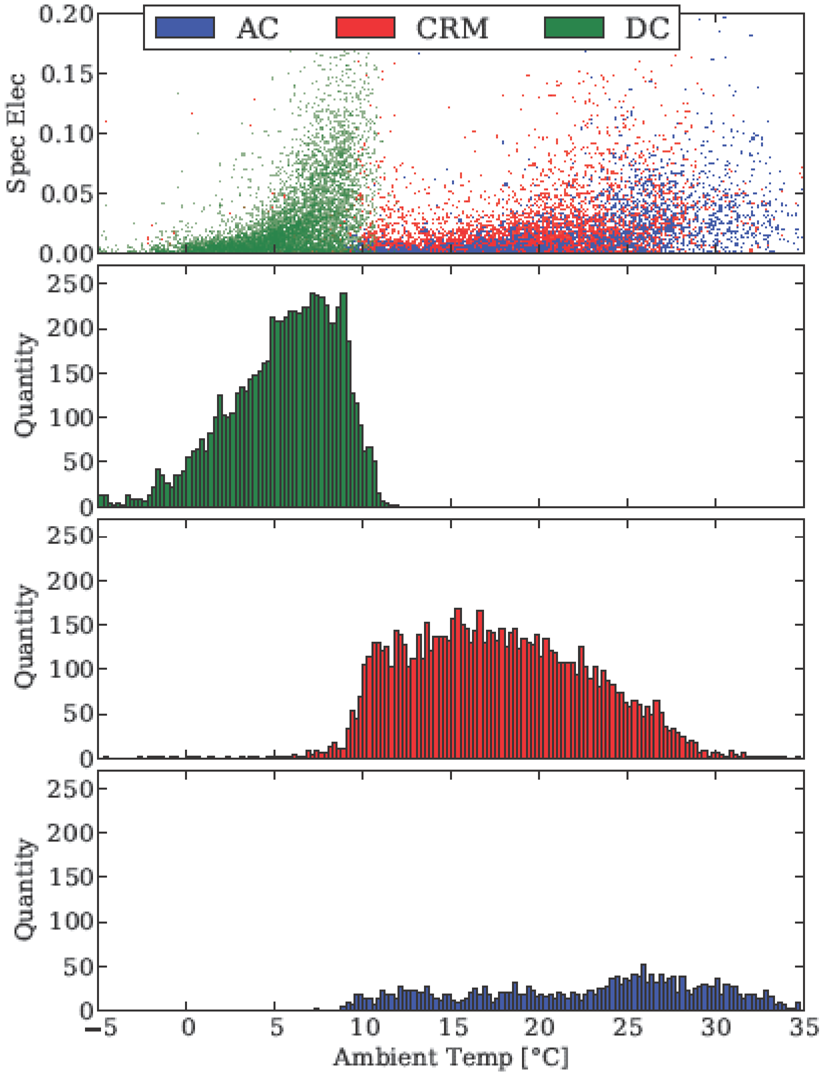

Figure 4: Specific Electricity Consumption (Spec Elec) of the Re-cooling Plant during its Operation caused by the Absorption Chiller (AC), the Compression Refrigeration Machine (CRM) and Direct Cooling (DC) and its Absolute Frequency

DC, the AC and the CRM are planned to be operated at different ambient temperature levels and the re-cooling plant is a three staged machine. If ambient temperature rises, first ventilation and later wet cooling is turned on. Therefore it is expected that the specific electricity consumption per unit of cooling energy grows when temperature rises. If this holds true the results of the PEF are not comparable and need to be considered against the background of the ambient temperature.

However, the data of Figure 4 show that this assumption is only valid to a certain extend. Here the electricity consumption of the re-cooling plant is allocated to the operation of the different chillers. The electricity consumption caused by DC is often higher than the consumption caused by the AC and the CRM, although the AC and DC are operated at higher temperature levels. Furthermore the AC is also operated at lower temperatures than planned. Therefore the comparison of the results is possible.

The primary energy consumption of the pumps impacts the results for the PEF mainly at lower output levels. This is shown by the difference of the first and the second row of the graphs of Figure 3. It is due to the fact, that most of the pumps are not automatically controlled, but set to a fixed flow rate (cp. Chapter 4.2) and their high electricity consumption at this point: The pumps of the AC have a total power of 20.2kW, those of the CRM have a total power of 18.8kW and those of the DC have a total power of 14.6kW (cp. Chapter 3.5). Therefore the impact on the result of the AC is again higher than that on the results of the CRM, as the power of the AC's pumps is 2kW higher than that of the CRM. The impact on DC is the smallest one.

Overall pumps have the highest impact on the results of the PEF, though at low levels. As operating times are mainly at these load levels, further verification of the optimisation potential seems to be worthwhile. The process in the components of the chillers themselves has the second biggest and the re-cooling plant the lowest impact on the PEF.

4.2. System analysis

Table 2 gives an overview of the average efficiency of the system components of the regarded period. These are the results of the machines operating states. Therefore stand-by losses are not considered.

Table 2: Efficiency of the Components

Component	*Efficiency*
Absorption Chiller	*69%*
Compression Refrigeration Machine	*4*
Direct Cooling	*10*
Re-cooling Plant	*18 (AC: 20, CRM 26)*
Combined Heat & Power Plants	*85%*
High Temperature Buffer Storage	*96%*

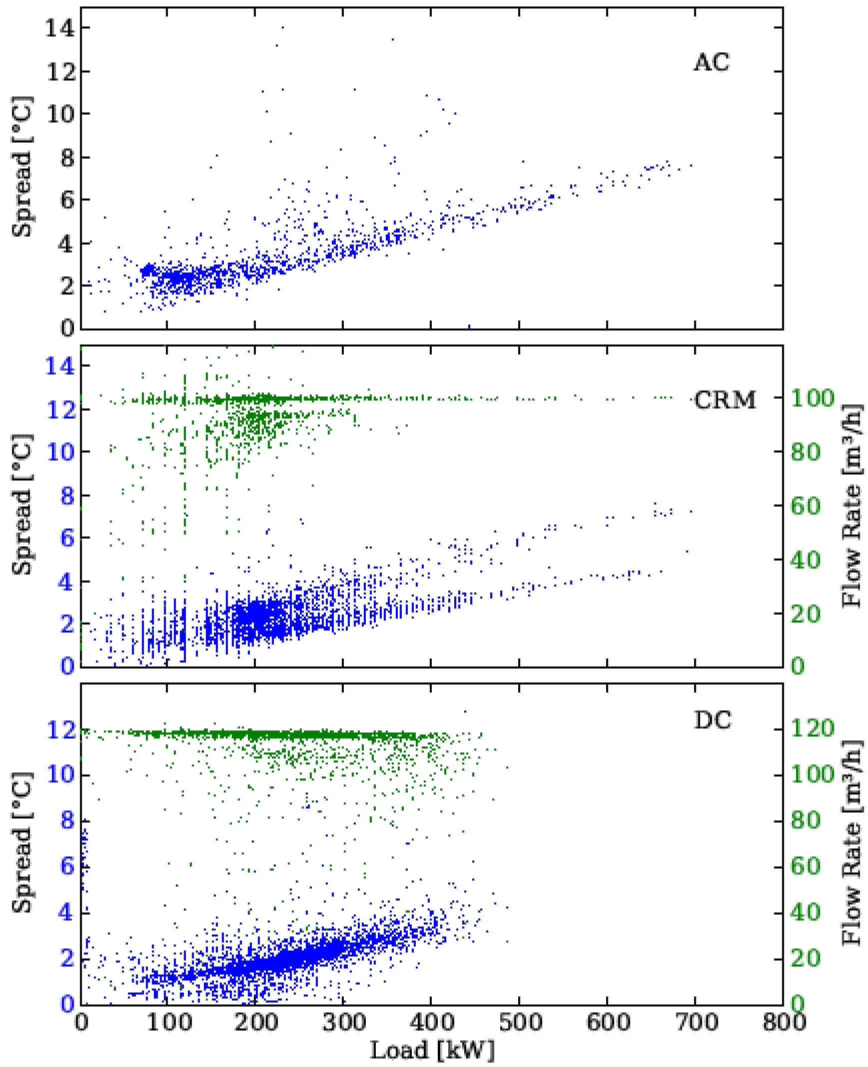

Figure 5: Spread and Flow Rate of the Re-cooling Water of the Absorption Chiller (AC), the Compression Refrigeration Machine (CRM) and Direct Cooling (DC)

The analysis of the system parameters - inlet and outlet temperatures, spreads and flow rates - shows that efficiency can be increased by flow rate control. For instance, Figure 5 shows the spread and flow rate of the re-cooling temperature for the different cooling options. For most of the time the flow rate of the CRM and DC is at a constant level of $100m^3/h$ or rather $120m^3/h$. All spreads and - what is not shown - all outlet temperatures of the machines are increasing with increasing load level. Only inlet temperatures stay constant. The spread of the planned 6°C is hardly ever reached. If flow rates were controlled electricity consumption of the pumps could be reduced. This is just one example. Planned spreads of the cooling water of the CRM and the AC are not reached due to the same reason. The outlet temperatures at the cooling water side of the AC, the CRM as well as the DC are with more than 10°C more than 2°C above the planned 8°C.

The spread of the inlet and outlet temperature at the heat side of the AC with more than 30°C is double the planned value of 15°C. Figure 6 shows its source, the parameters of the CHPs. Their temperatures are spread widely. The outlet temperature of the high temperature heat of 95°C is not always reached. However, the measured spread is more than the planned 15°C.

The outlet temperature of the low temperature heat of 50°C is most of the times not reached. In the load interval from 250 to 650kW, its measured outlet temperature is between 30 and 50°C. However, the spread is often above the planned 6°C. Two levels of flow rates can be identified. The flow rate leaps to the second level when the second CHP is turned on.

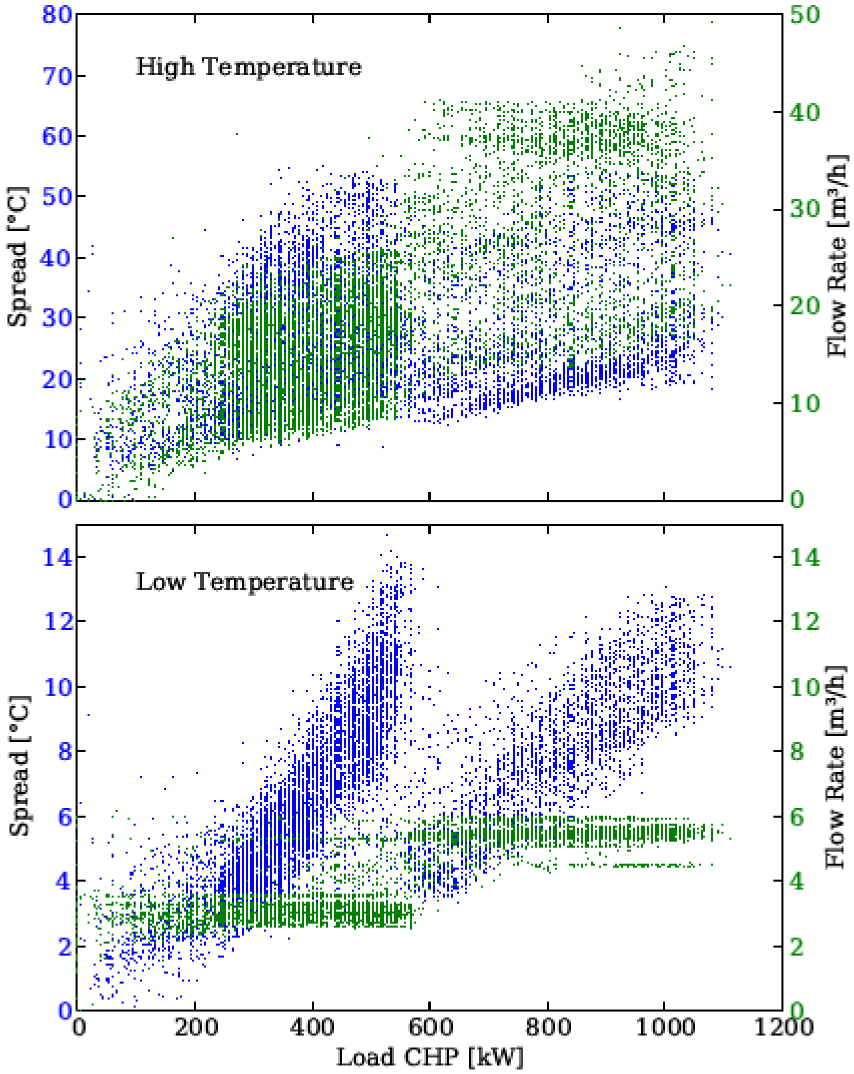

Figure 6: Spread and Flow Rate of the Combined Heat and Power Plants' High Temperature Heat

Another option for increasing the system efficiency is to lower the re-cooling temperature of the CRM and the AC. As an example Figure 7 shows that most of the time the re-cooling temperature of the CRM is above the ambient temperature. As the efficiency of the re-cooling plant is higher than that of the CRM, its capacity should be used as far as possible.

Figure 3 shows, that efficiency rises with increasing load level. Against this background and the fact that low temperature cooling energy is first stored in a buffer storage before it is consumed, intermittent operation might be an option to consider. Measured outlet temperatures of the cooling water of the chillers and the control parameters of the building's automation system show that the actual storage capacity is higher than the planned 9kWh. For the operation of DC it is 42kWh and for the operation of the CRM it is 28kWh. As Figure 3 shows, chillers are operated most of the time below the load level of 300kW. Therefore increasing load level would result in operating the chillers above 300kW. However, even if a capacity of 42kWh is assumed, loading time would be about eight minutes at this level and only three and a half at the load level of 700kW. Therefore this is no option at the present operating parameters. However, these depend also on the requirements of the consumers. Consequently, an analysis of the demand side might change the outcome.

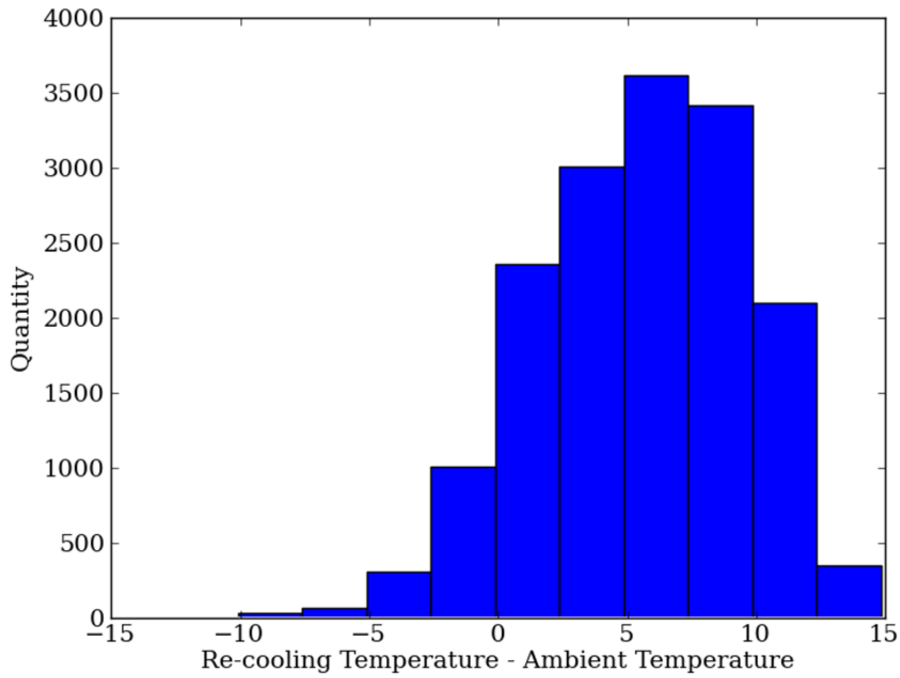

Figure 7: Difference between the Re-cooling Temperature of the CRM and the Ambient Temperature and their Absolute Frequencies

5. Conclusion and Outlook

In terms of primary energy consumption and with the underlying operating parameters first DC and if demand exceeds the capacity of DC the AC should be operated at present. As the pumps have the biggest impact on the results of the PEF and the system analysis has shown that this is due to constant flow rates, it is recommended to control all pumps automatically. As the necessary hardware is already installed, only the suitable strategy has to be implemented in the building automation control system.

Furthermore energy efficiency can be increased by decreasing the inlet temperature at the re-cooling side of the AC and the CRM.

Intermittent operation is no alternative to chose. However, further integration of the demand side into a further analysis might change this.

Against the background of a changing energy system leading towards an energy supply with an increasing share of renewable energies, the importance of energy efficiency of the regarded system itself will increase. Therefore Figure 8 shows the results of the PEF of the systems with an underlying PEF of one. This assumes that all input comes from renewable resources.

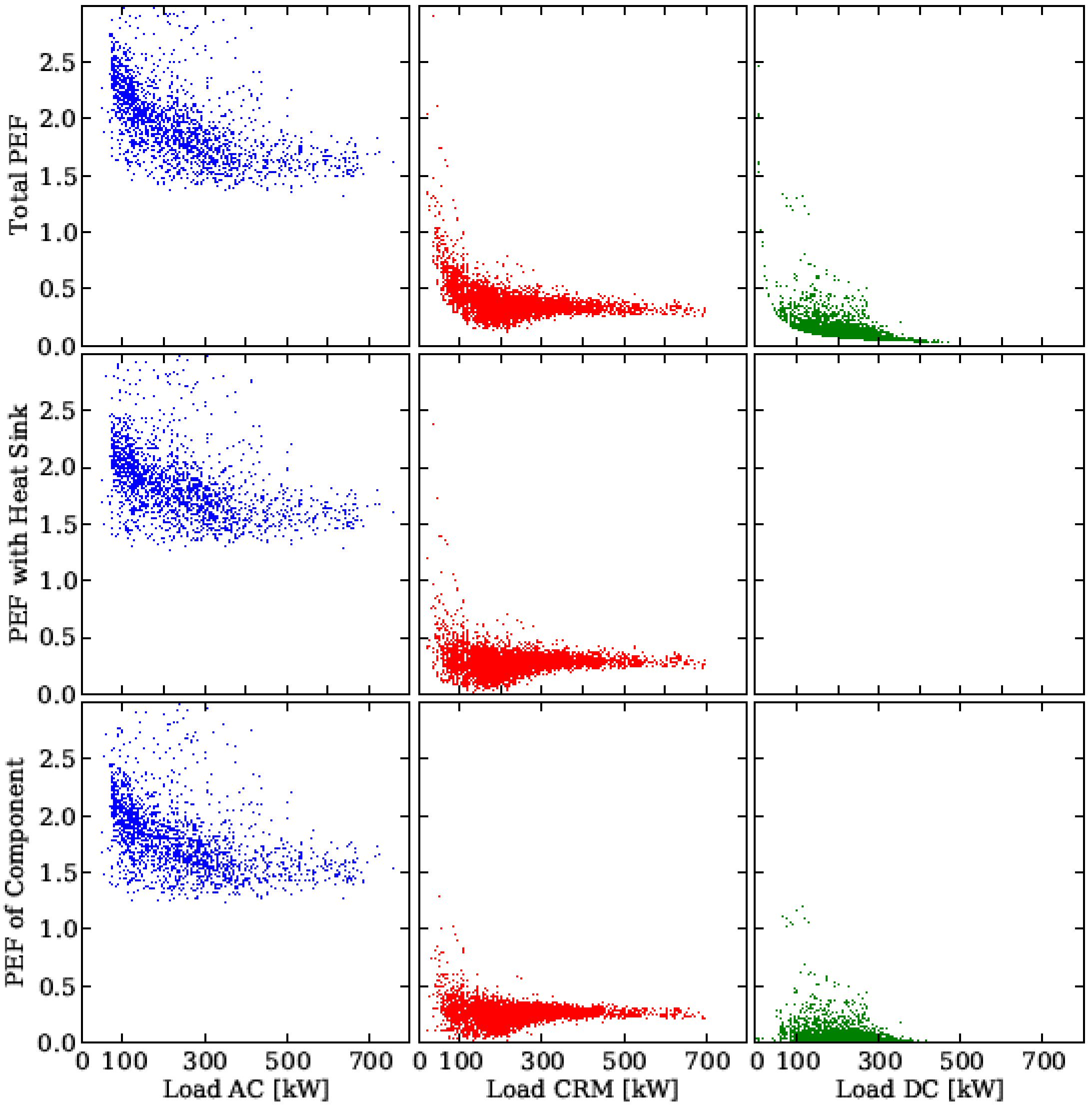

Figure 8: Calculated Future Primary Energy Factors of the Absorption Chiller (AC), the Compression Refrigeration Machine (CRM) and Direct Cooling (DC) at Different Load Levels based on Measured Data

DC still is the source with the lowest primary energy consumption. However, the AC will not be efficient in future unless the operating parameters will change. Its PEF is for all load levels above the maximum PEF of the CRM. Therefore using an AC like this seems to be only a temporary option.

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SUSTAINABLE SCHOOL BUILDINGS: SOME OF THE LATEST DUTCH EXAMPLES OF NEARLY ZERO EMISSIONS BUILDINGS

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ABSTRACT

In the Netherlands with respect to sustainable educational building there is a continuous development going on from sustainable building, to Passive House schools, to nearly Zero Emission Buildings to even Energy positive buildings. The Dutch government started a special funding program to stimulate the innovation of high performance schools. Some of these schools were built as extreme sustainability friendly schools while also much attention was given to comfort and health aspects. Three of these new schools were investigated: two passive house schools and the first net ZEB designed school are analyzed, measured and their results were compared with 13 other recent but more traditional designed schools, as well as with schools from earlier research. The results showed that concerning Indoor Air Quality and thermal comfort the new environmental schools did not perform very well. This is a disappointing result which indicates that is necessary to pay enough attention to the basic functionalities of a school (health and comfortable indoor environment) instead of focusing too much on sustainability.

INTRODUCTION

Indoor Air Quality and thermal climate in schools are problematic in many countries [Smedje et al.1997, Heath and Mendell 2002, Daisey et al.2003, Shendell et al 2004, Mendell and Heath 2005, Mi et al.2006, Kurnitski 2007, Clements-Croome et al.2008]. For Indoor Air Quality there is more and more attention, but often there is little or no focus on the thermal climate in schools [Landrigan 1997, Daisey et.al 2003]. As the energy use of school buildings became a critical factor in the design as the sustainability demands are getting tighter. However although energy is very important we should not forget the comfort needs, necessary attention level and health of the vulnerable children as they spent a large part of their time in school. Therefore it is very important that the thermal comfort and Indoor Air Quality of a school are good.

Ventilation

Indoor Air Quality in schools is primarily evaluated by CO_2-concentrations. ASHRAE Standard 62-1999 recommends an indoor CO_2-concentration of less than 700 ppm above the outdoor concentration, which means around 1200 ppm, to satisfy comfort criteria with respect to human bio effluents. Dutch schools have to meet the Dutch Building Code, which recommends a level of 1000 ppm CO_2-concentration with a maximum of 1200 ppm. The air change rates are mostly fixed values which do not take into account the effect of the external air pollution [Hani et al 2011]. The European indoor climate standard EN15251: 2007 provides different allowed CO_2 levels depending on the external air CO_2 concentration. However also in this standard the air change rates are still constant. Table 1 presents the CO_2 values according to the EN15251. The latest Dutch design guide, ISSO publication no. 89 [ISSO 2008] should lead the path to better IAQ in schools, see Table 2.

Table 1. CO_2 levels according to the EN15251

Category	Respective CO_2 level exceeding external air concentration in ppm for energy calculations
I	350
II	500
III	800
IV	> 800

Table 2. Different classes for IAQ regarding CO2-content

Class	A [Very good]	B [Good]	C [Acceptable]	D [Insufficient]
CO_2 content [ppm]	%of total school hours < 800	% of total school hours 800 - 1000	% of total school hours 1000 - 1200	% of total school hours > 1200

However if we look at the results of earlier Dutch studies on school ventilation [Zeiler and Boxem 2007], see table 3, it shows that there is no adequate Indoor Air Quality on quite a number of schools. If we look at other international research on ventilation in schools we that the situation is not much different. Mercier et al. found in their research on hybrid ventilation in Nordic schools that the measured carbon dioxide levels in classrooms ranged from 1150 – 1550 ppm, which was over the recommended limit [Mercier et al. 2011]. In Germany the situation is not much better [Hellwig 2010].

Table 3. Dutch studies: CO_2 levels in schools [Zeiler and Boxem 2007].

Study	No. schools	CO_2 levels ppm	
		Average	Range
1984	11	1000	500-1500
1990	6	1290	950-1950
1995	6	1320	700-2700
1997	96	990	425-2800
2004	5	1220	480-2400
2004	11	1580	450-4700
2005	6	1355	550-3000

Thermal comfort

For Indoor Air Quality there is more and more attention, but often there is little or no focus on the thermal climate in schools [Landrigan 1997, Daisey et al. 2003]. There is good evidence from literature that moderate changes in room temperature, even within the comfort zone, effect student's abilities to perform mental tasks requiring concentration, such as addition, multiplication, and sentence comprehension. Jago and Tanner [1999] made a short historical overview and found that already in 1931 the New York State Commission on Ventilation [1931] conducted major investigations into the physiological and psychological reactions to various atmospheric conditions by school children in classroom settings. Some of their findings showed that temperatures above 23,9 ºC produced such harmful effects as increased respiration, decreased amount of physical work, and conditions favourable to disease.

A more recent study is by Wargocki and Wyon [2007a] who determined whether avoiding elevated temperatures in classrooms can improve the performance of schoolwork by children, and if so, by how much. They concluded that reducing moderately high classroom air temperatures in late summer from the region of 25°C to 20°C by providing sufficient cooling, improved the performance of students on two numerical tasks and two language-based tasks resembling schoolwork. Improvement mainly occurred in terms of the speed with which these tasks were performed, with almost no effects on errors. A fairly good agreement in terms of the effects on performance was obtained between two independent experiments, in which children's thermal sensation decreased from slightly too warm to neutral, carried out one year apart. In addition, their experiments investigated the effects of increased outdoor air supply rate on the performance of schoolwork by children as a continuation of two other experiments in the same series, reported in a separate paper by Wargocki and Wyon [2007b]. Their results both confirm and supplement the findings of thermal effects on children's schoolwork performance that were obtained in the above mentioned studies about thermal effects on school performance in the moderate temperature range. The observed effects of increased ventilation rate and reduced temperature on the performance of schoolwork by children by Wargocki and Wyon [2007a] are larger than reported effects on the performance of office work by adults [Wyon and Wargocki 2006a-c]. They conclude that this indicates that children may be more susceptible than adults to environmental conditions.

Overall, warm temperatures tend to reduce performance, while colder temperatures reduce manual dexterity and speed. Many studies have revealed that the thermal environment in the classroom will affect the ability of students to grasp instruction. There for it important not only to look at the energy consumption and Indoor Air Quality, but also at the thermal comfort performance of schools.

METHODOLOGY

Three very recent built sustainable designed schools were analyzed and the results compared with other more traditional schools as well as a series of modern schools. To investigate the results of the sustainable schools measurements were done concerning thermal comfort and indoor air quality. During a week different measurements in schools were undertaken to be able to define the quality of indoor air quality and thermal comfort.

The Veldhuizerschool

The Veldhuizerschool in Ede is the first passive school in the Netherlands. The construction of the school was finished in July 2011. Build according to the passive house principle means extreme airtightness, highly insulated with a Rc = 10 m²K/W, triple glazing and on top the school has a green sedum roof .

Figure 1 The Veldhuizer school and classroom

The conditioning is done by individual room ventilation systems with heat exchangers. The pupils, as well as all the electrical equipment [e.g. computers, monitors, etc], contribute to the heating of the school. The air distribution is by textile ducts, see Fig. 2. Only during start-up of the lessons heating energy is needed, the rest of the day the students generate enough heat to warm the classroom. This results in an energy consumption which is almost 75% less than traditional school buildings.

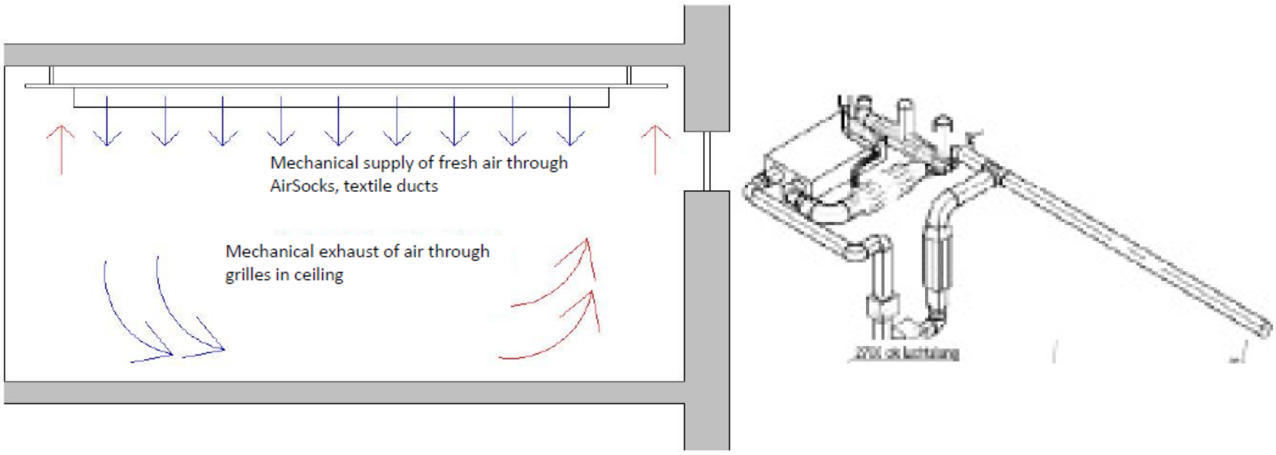

Figure 2 Indoor principle of Veldhuizerschool, Ede

Christiaan Huygens College: an energy plus school

Christiaan Huygens College is the first CO2-neutral and energy plus school in the Netherlands, see Fig. 3. The new building uses a compact construction in order to limit the surface area of the façade, thus reducing excess heat in summer and heat loss in winter as much as possible. At the same time, well-insulated windows allow natural daylight to flood the building without causing overheating. Thanks in part to the Energy Roof, a combination of PV and thermal collectors integrated into its roof cover, the school building generates more energy than the school needs for its own use. The indoor climate is regulated with a floor heating / cooling system with a ground source heat pump. A balanced ventilation system, see Fig. 4 is used to provide sufficient fresh air in the classrooms and this can be used for additional cooling during the summer.

Figure 3. Christian Huygens College Eindhoven: the first energy plus school, Large central atrium within the school and Class room

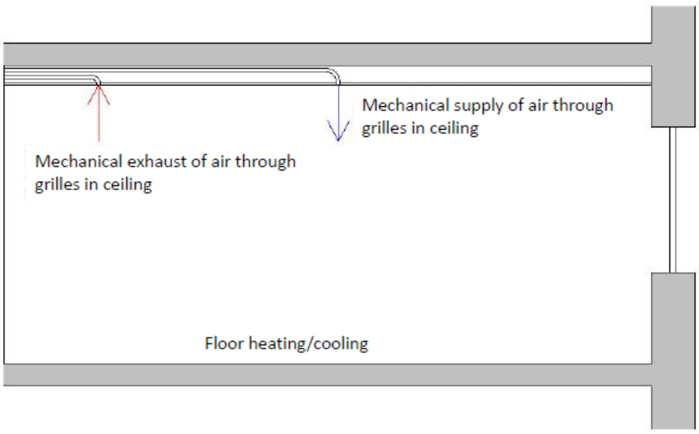

Figure 4. Indoor principle of Christiaan Huygenscollege, Eindhoven

OdyZee school: a NZEB passive house school

In 2009 the Dutch government started the so called UKP NESK program to stimulate innovation for energy neutral buildings. UKP means unique chances projects and NESK means 'Towards energy neutral schools and offices' [Naar Energieneutrale Scholen en Kantoren]. This program of the Dutch government gave funding to projects which show exceptional innovation in the area of energy conservation, sustainability or organization within the building industry. These are the most interesting projects in the field of NZEB in the Netherlands. The OdyZee school is the first school within the UKP NESK program that was finished, see Fig. 5. The energy concept of the school is based on applying the Passive house-concept, with an average insulation with a Rc-value of 10 m2W/K and triple glazing. The school has a ground source heat pump, low temperature floor heating system, balanced mechanical ventilation with 85%heat recovery and a solar boiler. IAQ is control on a maximum CO2-level of 800 ppm. The Energy Performance Coefficient value is 0.54, which will be reduced to zero after installing 500 m2 PV panels.

Figure 5 OdyZee school built conform the Passive house concept and Class room of the OdyZee school

The building of the OdyZee school is executed as a passive school. This means that the façades have a high thermal insulation combined with extreme air tightness. The school is equipped with a balanced ventilation system which should ensure a healthy indoor air quality, see Fig. 6. The building is designed to become class A ventilation.

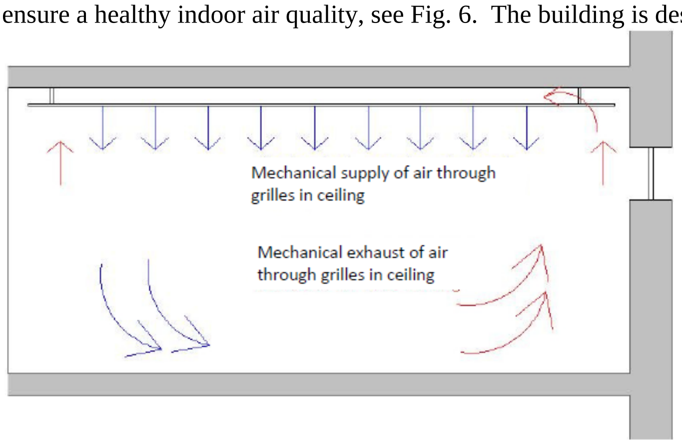

Figure 6 Indoor principle of SO/VSO OdyZee, Goes

MEASUREMENTS

One classroom in each school building was selected for measurements in the heating season during one week. The Equipment specifications are shown in table 5 and which include measurements of air temperature, radiant temperature, relative humidity, air velocity and CO_2 concentration. The different sensors were placed a tripod put in the middle of the classroom, see Fig. 5

Table 4 Measurement periods

School	Location	Measurement period
A	Ede	07-03-2012 till 14-03-2012
B	Goes	26-03-2012 till 02-04-2012
C	Eindhoven	03-04-2012 till 12-04-2012

Figure 7 Measurement pole setup

Table 5.Measurement equipment

Type of measurement	Equipment	Brand	TU/e ID	Range
Temperature	Sensor	EE80	2335	0° - 40°C
Radiant temperature	Black sphere PT100	-	612	-100° - 300°C
Relative humidity	Sensor	EE80	2335	0 - 100%
Air velocity	Omni speedometer	Sensor HT428	708	0.05 - 5 m/s
CO_2 -concentration	Sensor	EE80	2335	0 - 5000 ppm
Log data	Data logger 2F8	Grant 2020 series	1816	n.v.t.
Process data	Laptop	Dell Latitude C840	1629	n.v.t.

RESULTS

Ventilation

Since the IAQ inside the schools is one of the main subjects in this research, it is interesting to look at the differences in IAQ between the three investigated schools. The graph given below [Fig 8] is a representation of the CO_2 concentration in all three schools during one school day from 08:00 in the morning till 17:00 in the afternoon.

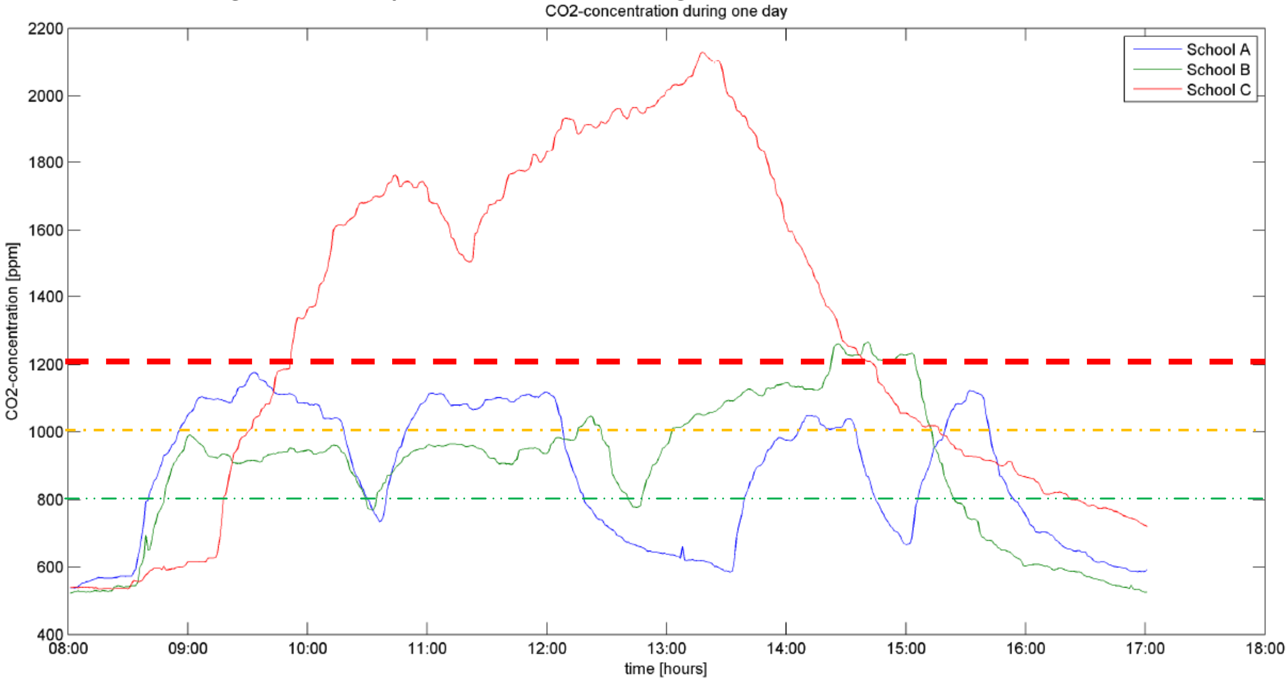

Figure 8 CO2 concentrations during one school day

When looking at these results, it becomes visible that the IAQ of school A and B for the largest part of the school day, is between 800 and 1200ppm, which means that the IAQ of these schools most of the time corresponds to class B/C. Looking at school C, a large peak with a CO2 concentration over 2000ppm is visible, around midday, see Table 6. This means that for a large part of the day the IAQ of school C corresponds to class D, which is undesirable. The table below depicts the distribution of school hours for each school in the different IAQ classes.

Table 6 Actual IAQ class of each school

Class	A [Very good]	B [Good]	C [Acceptable]	D [Insufficient]
CO_2 content [ppm]	% school hours < 800	% school hours 800 - 1000	% school hours 1000 - 1200	% school hours > 1200
School A	32%	22%	46%	< 1%
School B	15%	47%	32%	6%
School C	28%	12%	10%	49%

Temperature

What we found from our measurements is that the average temperature during classes is ranging from on average 20.7 °C(A, Fig. 9) , 21.6 °C (C, Fig. 11) up to 23.2 °C (B, Fig. 10). This is clearly much too warm given the fact that this was during a winter period. If we look at the control strategy we find different solutions depending on the kind of heating system applied. The two schools with floor heating show a slow decreasing characteristic whereas the heating up is almost as fast as that of the all air system of school A. School A is controlled on a minimum temperature of 19.5 °C, which is conform the guidelines, whereas school B and C never reached their minimum control room temperature to activate the heating system. The process control responds of school A is fluctuating within almost 0.5 °C, which is an excellent result. By reducing the temperature setting at the start of the classes the temperature shift of plus 2 °C might be reduced even further. The temperature control of achool B and C are less good and show an overshoot of almost 3 °C on a already too high night temperature of 21.3 °C respectively 20.3 °C. This clearly shows that slow responding heating systems like floor heating are not a suitable solution for schools with their fast changing internal loads at the beginning of classes due to the high density of pupils in the classroom and the resulting high internal heat load. In school the average temperature during classes is with 23.2 °C just too high and outside classes the rooms should be ventilated more with fresh outside air.

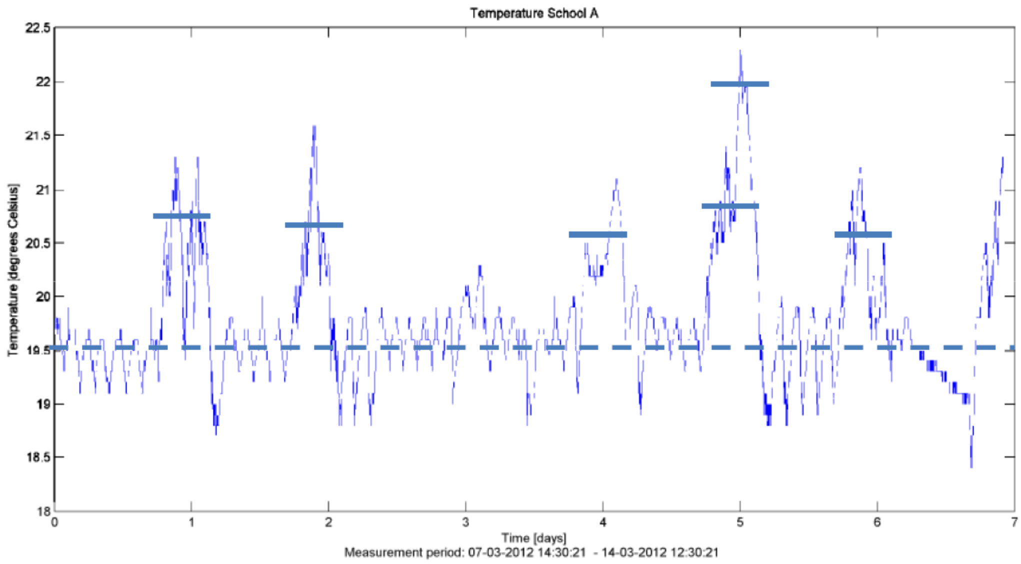

Figure 9 Indoor temperature during complete measurement period school A

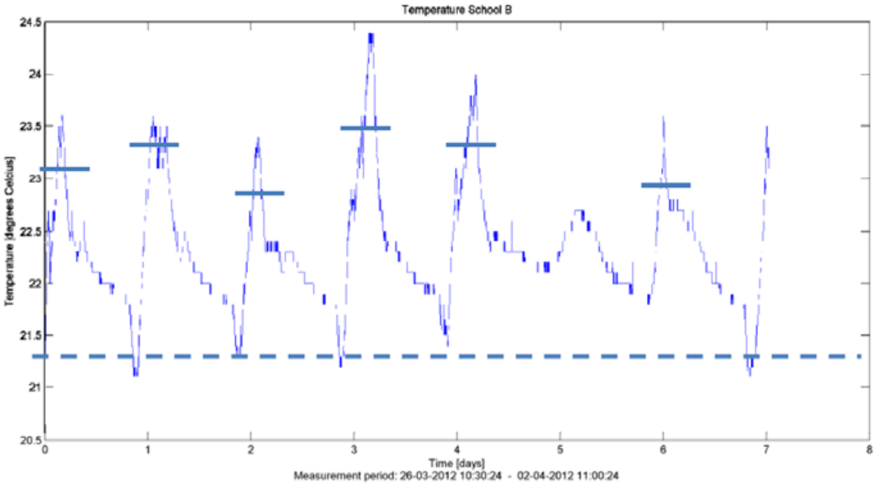

Figure 10 Indoor temperature during complete measurement period school B

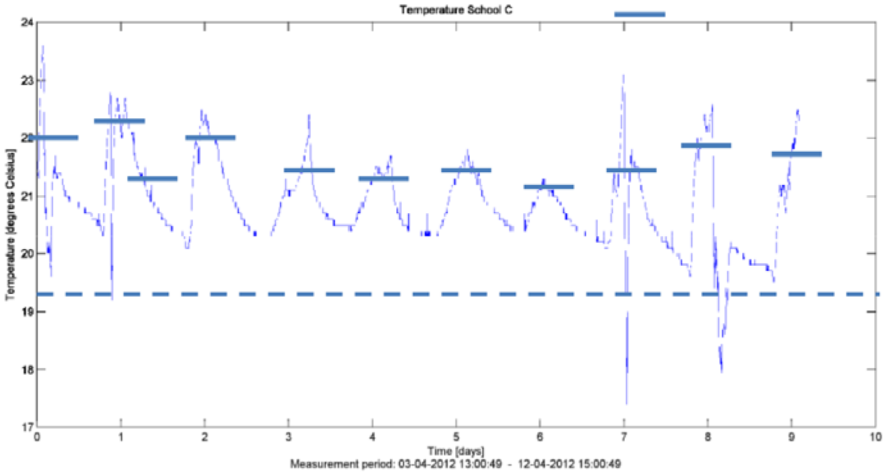

Figure 11 Indoor temperature during complete measurement period school C

DISCUSSION

In earlier research by van Dijken (2004) 11 schools were investigated on their Indoor Air Quality. This study gave the percentage of school time in which the CO_2 concentrations are above 1200 ppm, which determines the percentage of time in which the Indoor Air Quality inclass D (insufficient IAQ). In a recent report by the Dutch society of architects, BNA, ten recently completed more traditional designed and built schools were examined on the aspects of IAQ and thermal comfort [Grosveld 2011]. This gave us another opportunity to compare our results of the three highly sustainable designed schools [A,B and C] with results of more traditionally designed schools. Important is to conclude if the new schools reach an sufficient level of Indoor Air Quality confirm the Dutch ISSO 89 guideline. Fig. 12 represents the percentage of time time that the CO_2 concentration is higher than 1200 ppm, so when the Indoor Air Quality is not good enough. It shows clearly that there has been made progress if we look at the percentage of class hours which do not have an adequate level of CO_2 concentration: average study by van Dijken 67%, average by BNA 14.7 % and average of sustainable schools 19%. There are still important lessons to be learned. Maybe the new REHVA guidebook on Indoor Environment and Energy Efficiency in Schools [d'Ámbrosio Alfano et al. 2010] can provide some help. It gives an overview on the main aspects of and critics on school buildings envelope and system design, aiming to obtain comfortable and energy sustainable indoor environments for schools [Lanniello and d'Ambrosio Alfano 2010].

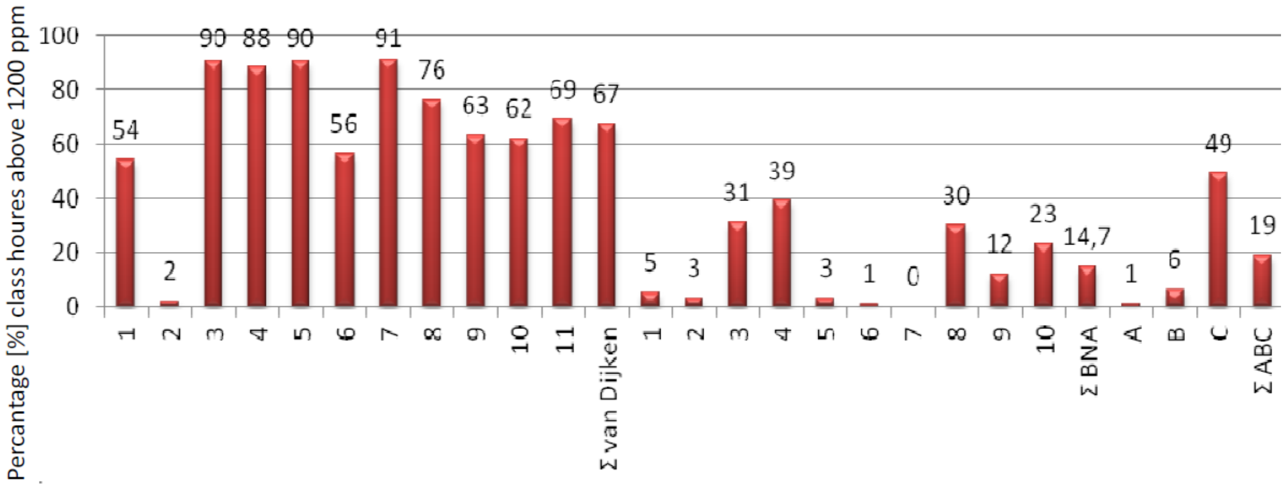

Figure 12 Comparison of percentage that the CO2 concentration is above 1200 ppm.

CONCLUSIONS

We presented the latest developments on sustainable school design in the Netherlands. We looked at what are reasonable IAQ levels for classrooms and presented the Dutch standard for IAQ in classrooms. This enabled us to compare the measurement results of three recent completed sustainable schools with the IAQ standard. The IAQ of the three sustainable schools is not much better than schools based on more traditional design approaches in relation to the Indoor Air Quality. This research gives an introduction on the importance of a good thermal indoor environment in schools for the performance of students. It is clear from recent research and research in the past that temperatures in classrooms are important factors in the learning process and improving thermal comfort should be given more attention. In 3 of the latest sustainable schools the Indoor Air Quality and thermal comfort were examined and results compared with results of two series measurements in more traditionally designed schools. The sustainable schools did not outperform the more traditional designed recent completed schools of the BNA study. We can conclude however, that there is made an impressive improvement in comparison with older schools, like those in the study by van Dijken. Clearly there is more knowledge and insight on how to improve IAQ, however focusing on sustainability lead to slightly less good IAQ. This indicates that a school design team should not only focus on sustainability but first of all should pay attention to reach an adequate Indoor Air Quality and good thermal comfort for the school.

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THE HUMAN LEADING THE THERMAL COMFORT CONTROL

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ABSTRACT

Many buildings were designed and calculated by advanced software tools and simulation tools. However in real practice these buildings do not achieve the calculated energy efficiency, but use up to 40 to 50% more energy. One of the reasons for the discrepant ion between designed performance and real performance is the human behavior of which no real adequate integration into the design tools exists Therefore new design approaches are needed to implement the real behavior of occupants of buildings. Human-in-the-loop Technology is developed; a technology to implement user behavior. By starting from the human perspective and use available and new technology, we determined the critical performance indicators for the perceived human comfort. To further optimize the performance of these systems, further development is done into the possibilities and use of infra red heating systems for individual comfort control on workplace level.

INTRODUCTION

There is growing evidence that many, especially sustainable, designed buildings do not, in practice, meet the intended levels of energy performance (Tetlow et al. 2012). The subject of energy has become increasingly contentious with the current energy prices and the strict emissions targets for the future (CIBSE 2012). In fact, energy consumptions are frequently two times the design expectations; this discrepancy has been termed the ‘performance gap’ (Bordass et al. 2004). This situation is the result of the applied energy modeling calculations conform building regulations and rarely consider the real in-use performance and, in particular, the actual behaviour of the building occupants (Tetlow et al. 2012). Designers look at regulated loads whereas facilities managers look at the whole energy bill including unregulated loads, representing the real occupants’ behaviour(CIBSE 2012). Traditionally, during the design process the construction industry has considered the building occupants often superficially. Efforts to reduce the energy consumption caused by the building occupants have largely revolved around the ‘information deficit model’ which assumes that people will both interpret information as intended and act rationally to modify their behaviour accordingly. This somewhat simplistic approach to the behaviour of the building users has been shown to be largely ineffectual (Owens & Driffill, 2008) and there is now a growing realization that delivering sustainable, healthy buildings will require a greater appreciation of how the occupants interact with their environment (Tetlow et al. 2012). Clearly, the building occupants behave more complex than current standard design models allow for. The human behaviour can influence the energy consumption by more than 100% (Brohus et al. 2010, Parys et al. 2010), so therefore it is necessary to incorporate the human needs better in the control strategies. Sensing, monitoring and actuating systems in relation to the user perception and preferences play the key role in reducing overall energy consumptions in buildings. Optimized process control is a necessity for the improvement energy performance of buildings (Yu et al 2007). Overall the role of the occupant in relation to the energy consumption has found to be important (Haas et al 1998, De Groot et al 2008). Reduction of or optimizing of energy use is often done without really taking in to account the goal of the energy consumption, human comfort. However energy reduction can only be achieved if user comfort is individually addressed (De Groot et al. 2008). Trying to optimize energy efficiency without addressing occupant comfort is not going to work (Nicol 2007). With smart energy efficient buildings the relation between human behaviour and energy consumption has become significant, and should be looked into by applying Building Energy Management Systems (Pauw et al 2009).

THE ‘HUMAN-IN-THE-LOOP’ APPROACH

One of the primary objectives of a heating, ventilation and air-conditioning system is to provide a thermally comfortable environment. A comfortable indoor environment for all the people in a building is difficult to reach because of individual differences between persons. Based on literature it is concluded that individual differences, including: age (Oeffelen 2007), gender (Karjalainen 2007, Choi et al. 2010), fat (Zhang et al. 2001), metabolism (Havenith et al. 2002) and clothing resistance (De Carli et al. 2007), are of importance for the individual experienced thermal comfort. However, nowadays still the Fanger comfort model (Fanger 1970) is mainly used to determine the (thermal) comfort inside office buildings. Individual preferences are not taken into account in this model. A lot of effort has been taken to design energy efficient HVAC systems. However, in practice the intended comfort level of these HVAC systems is not achieved, resulting in more sickness absence and lower productivity of the building occupants. This is mainly due to the fact that the control paradigm for HVAC systems has remained relatively unchanged, namely regulating indoor environmental variables such as air temperature without including the thermal state of the individual occupant in the control loop. The traditional thermal comfort models (see e.g. Fanger 1970) assume that people in buildings are passive recipients that are comfortable or not comfortable dependent of the momentary thermal environment (temperature, airspeed etc.), while others (e.g. Nicol & Humphreys, 1973 and Paciuk, 1990) argue that also occupant behaviour and feedback loops for personal control are essential for modeling indoor climate related man-environment relations (Claessen et al. 2012). For example Boerstra & Beuker (2011) concluded – after an analysis of 20 field studies – that office buildings in which occupants perceive to have adequate control over their indoor climate are more comfortable and have less building related symptoms. Reanalyzing the HOPE database (60 office buildings with over 6000 respondents), Boerstra et al. (2012) found correlations between buildings with more perceived personal control on temperature and increased thermal comfort during winter and with more overall comfort during winter and summer. Furthermore combinations of control options were found to be more effective at reducing the building related symptoms than single control options (except for control on noise). Their findings suggest that more perceived control over indoor environment will improve comfort and health of the building occupants (Boerstra et al. 2012).

HUMAN COMFORT AND COMFORT CONTROL

The most recent research on human comfort looks at local sensations of individual body parts (Zhang et al. 2010) and thermoregulation with skin temperature predictions (Munir et al. 2009). The interaction between indoor environment and skin is for normal office conditions largely determined by the mean radiant temperature and therefore there is a large effect of mean radiant temperature on the energy consumption in a comfort-controlled office (Kang et al. 2010). By optimizing the responses to the individual human comfort differences energy conservations of up to 25% are possible (van Oeffelen et al. 2010). The energy supply to a building must be related to actual dynamic changing comfort needs, behaviour of the occupants of the building and the behaviour of the building itself due the weather conditions. Therefore, more actual information is needed. The application of low cost wireless sensors offers new practical applicable possibilities (Neudecker 2010, Gameiro Da Silva et al. 2010). If so, then energy demand and energy supply could become more balanced and less energy wasted.

Measuring the radiating temperatures by a low cost Infra Red camera should make it possible by image post-processing to estimate energy fluxes and temperature distributions with comfort prediction. Correct temperature distribution measurements could be calculated by remote camera control and thermo graphic parameter correction (Revel and Sabbatini 2010). Thermal comfort for all can only be achieved when occupants have effective control over their own thermal environment (van Hoof 2008). This led to the development of Individually Controlled Systems (ICS) with different local heating/cooling options (Filippini 2009, Wanatabe et al. 2010). Our intention is to design and built an experimental workplace with an individual controlled heating/cooling panel in front of the workplace to test our specific approach to comfort and energy management. The implementation of such detailed dynamic approach to individual comfort control is new.

It is necessary to look more closely to the individuals on working space and personal level. So we do not look only to room temperatures and thermostat settings of heating or cooling devices, but really look into the dynamic parameters related to the individual thermal comfort, the actual occupancy, and the actual parameters of the building services installations and use of appliances.

ANALYSIS OF PERCIEVED HUMAN COMFORT

Literature shows that the hands are the most sensitive body parts for the human thermoregulatory system (Zhang 2003). In addition, upper-extremity skin temperature is a sensitive indicator of the body thermal state in the cooling region (Wang et al. 2007). Studies in the automotive field have shown that facial skin temperature is a measure for overall thermal sensation (De Oliveira et al. 2009). Both the hands and face are directly exposed to the environment and show potential to be remotely sensed.

Recently, individual controlled (HVAC) comfort systems were proposed, which can cope with the individual differences (e.g. clothing behaviour, body fat) between office workers. In addition, these systems focus on the body parts (hands, feet and head) which mainly dictate thermal discomfort in mild cool/warm office environments. A direct conditioning of these parts would be the most effective way to achieve thermal comfort. A set up of such a concept is shown in Fig. 1. The human body can regulate heat flow to the environment by increasing or decreasing the skin blood flow. During mild cool exposure vasoconstriction is the most important thermoregulatory effecter, which can be clearly observed in the upper-extremity region. In addition, the variations in facial skin temperature may also indicate if a person is getting warmer or cooler. The challenge for automatic control of radiant heating is to detect the turning point from a neutral thermal state to a cooler thermal state before the user perceives any cool thermal sensation. The fact that the skin temperature can fluctuate within a range of temperatures without producing any temperature sensation (i.e. the neutral zone) is highly useful in this.

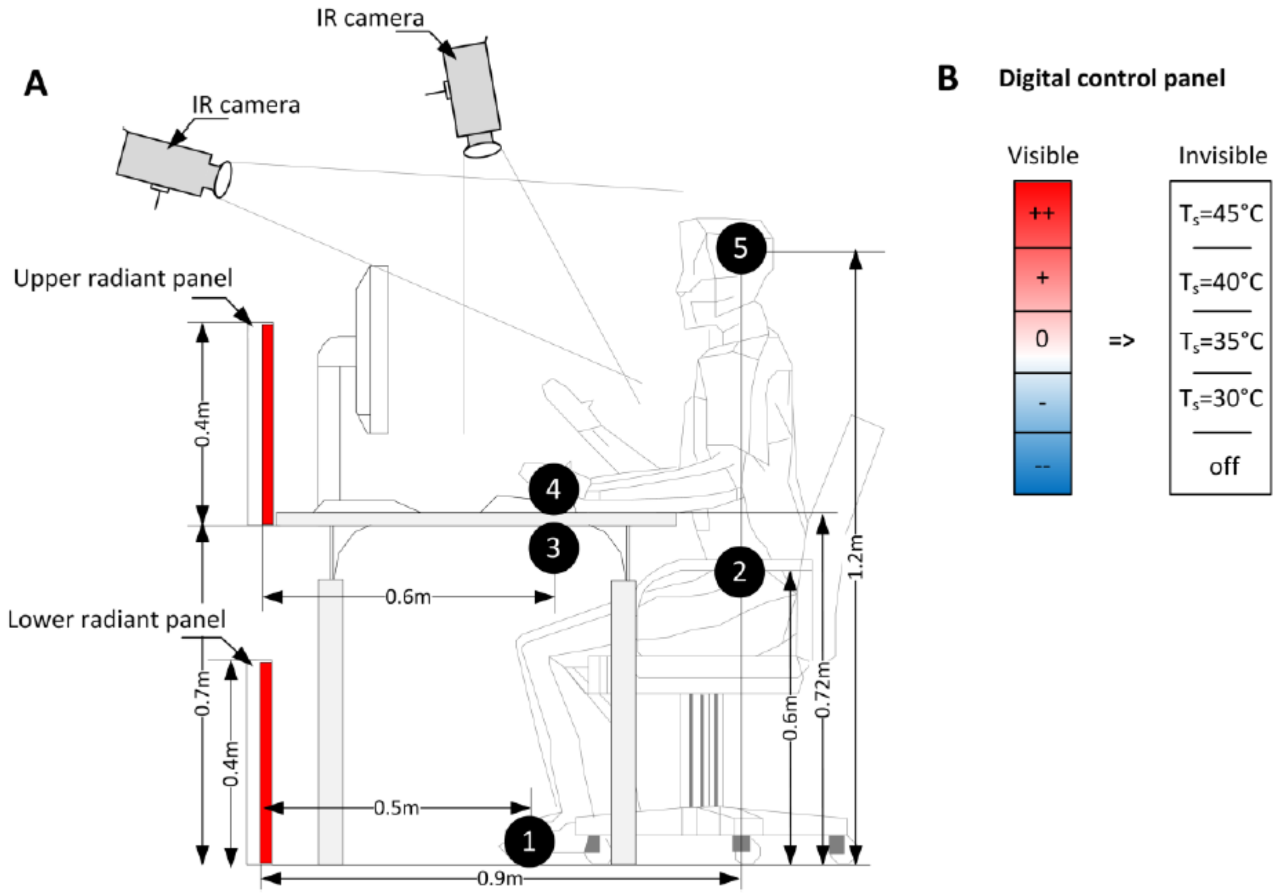

Figure 1. Experimental workplace set-up. for individual thermal comfort(A) local HVAC system consisting of two vertical mounted radiation heating panels, and (B) digital control panel. Two infrared (IR) cameras for skin temperature measurements and measurement positions (black circles) of local comfort parameters, where 1=feet, 2=abdomen, 3=desk, 4=hands and 5=head.

Experiments I: User-control proof-or-principle

A number of user-controlled experiments were performed, in mild cool conditions (Ta=19~20°C), in order to determine if a decreasing trend in skin temperature of the hands or face was observed, before the user performed any heating control action. The only intervention in the individual thermal climate was the use of individually controlled infra red heating panels. The panels were placed vertically in front of the office desk and therefore not optimized to heating the hands, see fig 1. Two human subjects participated in this research. The results ‘proof-of-principle’ demonstrated that the finger skin temperature was a critical performance indicator of the body thermal state in the cooling region. To test whether the finger temperature was actually useful as control signal, the experiments were reversed: from user-control to automatic control. The goal of these user-controlled experiments was to detect a feed forward transition out of the comfort zone, before the user took any control action. Results showed that this transition is quite difficult to detect. Standard fluctuations of 2 °C in finger skin temperature make it difficult to recognize a clear trend out of the neutral zone. Additionally, in some of the user-controlled experiments a decreasing trend in finger temperature is shown before the user had taken any control action. While in other sessions the decreasing trend was recognized too late, which means that subject already had taken a control action to compensate for his cool sensations. In almost all sessions, the radiant heating system was, despite of the maximum panel temperature (set by the user), not able to compensate for the cool whole-body sensations. Skin temperatures of the finger and hand did not return to the comfortable zone.

Experiments II: Automatic comfort control

An improved heating system was applied which radiates the heat more concentrated to the hands. This heating system consists of two incandescent reflector heating lamps (Philips R125 IR250) focusing each on one hand, see Fig. 2.

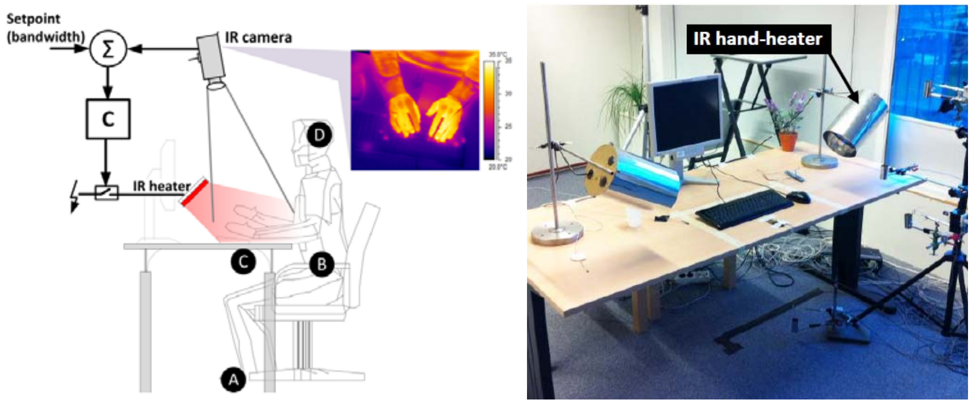

Figure 2. Local heating controlled by subjects' upper-extremity skin temperature, an experimental setting to measure the effect of individual controlled additional radiative heating.

The finger temperature, measured by IR thermography, was tested as feedback control signal for automatic regulation of a radiant hand-heating system by applying different set-points: the small, medium and large bandwidth. The bandwidth is defined as a range of skin temperatures in which the finger temperature was controlled. By controlling the finger temperature in a small bandwidth (Tsk=29-31.5°C), it was possible to feed-forward respond to user thermal preferences (i.e. before cool discomfort occurred), while the basic room air temperature was lowered from 22 to 19.5°C (Fig. 3).

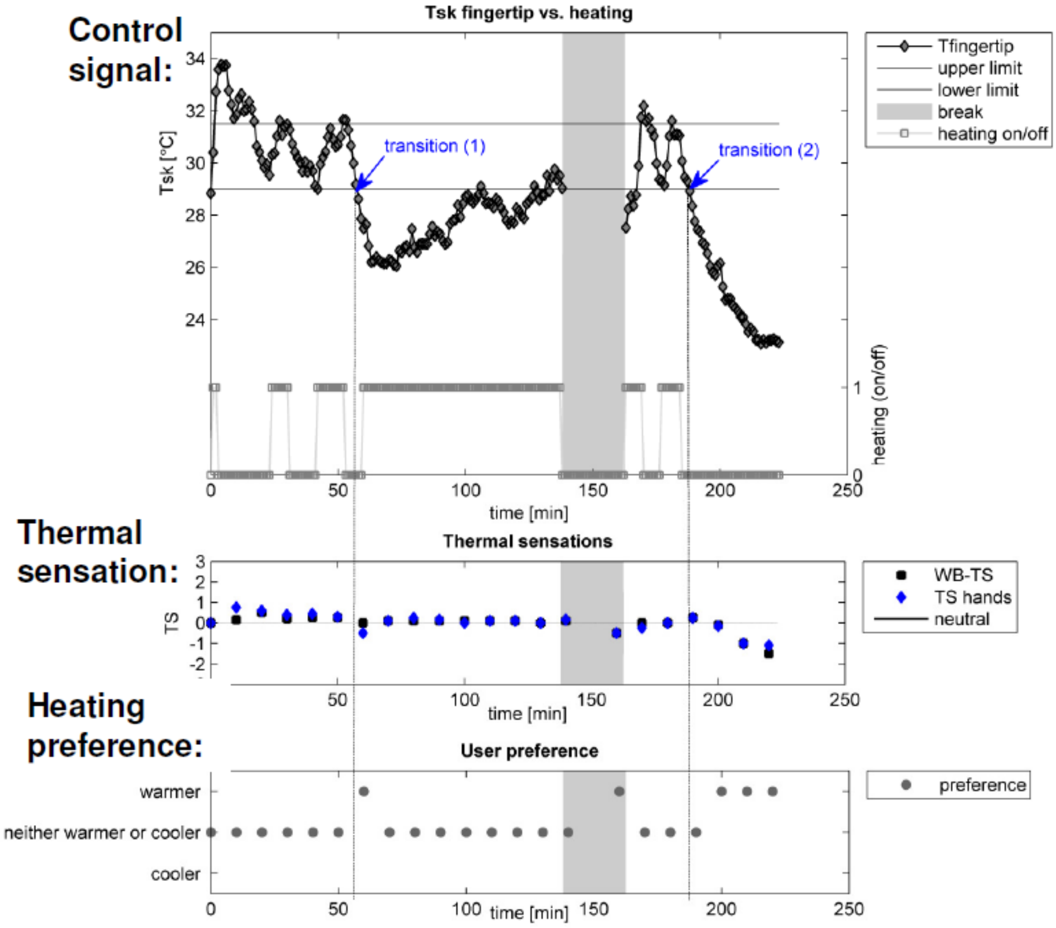

Figure 3. Upper-extremity skin temperature controlled in a small comfort temperature bandwidth with two transitions out of the bandwidth. Fingertip skin temperatures (moving average) versus heating level, whole-body and local thermal sensation, and heating preferences.

The local- and overall thermal sensation of the subjects were maintained at neutral or slightly higher level, and the subjects (n=2) did not prefer any environmental control action. A correlation between the finger temperature and overall sensation was found ($r2=0.45$, $P<0.05$). By modeling the preference that arises from the interactions with the user, this small bandwidth might be applicable to other individuals.

DISCUSSION

Where this research did not look at the comfort level by conditioning when the user is present, the building user comfort level should be looked into. The challenge is that the workplace should be right conditioned before the neutral thermal state turns into a cooler or warmer thermal state. When the skin is adapted to a certain temperature, the skin temperature can fluctuate between the borders of the neutral thermal zone without causing any thermal sensation. Wang (Wang et al., 2007) tested persons by exposing them to a slightly cool environment of 19 °C and warm environment of 28.2 °C. In the situation of the slightly cool environment the testes subjects voted their thermal sensation was cold between 10 and 20 minutes. In the warm environment the subjects voted warm after circa 10 minutes. This means that the building service systems must be capable of conditioning the workplace within 10 minutes, before the building user perceives warm or cold;

The achieved energy reduction by controlling the temperature on room level was 16% for heating and up to 28% for cooling compared with the actual situation.

The applied model to calculate the comfort is based on the PMV value. For the actual situation, where an uniform environment is assumed this PMV model could be said to be applicable, where it has the restriction that even with PMV of zero, there is 5% of the building users not satisfied with the environment. For the calculated PMV on room there are some points which can be discussed. This PMV does not take into account that it takes some time before cold conditions are perceived. With the possibilities of the user position detection it should be looked into if the room can be feed-forward controlled, so the building systems start with climatization before the occupant enters the room.

CONCLUSION

This article presents a new control strategy for automatic control of personalized radiant heating in mild cool office environments, by including the human body as sensor in the control loop. The upper-extremity skin temperature, remotely sensed by infrared (IR) thermography, was proposed as feedback control signals. The objective of this control strategy is to save energy, while maintaining thermal comfort of the individual building occupant. Improvement of the energy consumption was made possible by enhancing individual comfort of occupants (individual comfort control strategy) and incorporation of their behaviour (wireless sensor position determination). By starting from the human perspective and use available and new technology, the outcome will be more focused on the ability to understand the critical aspects of the comfort of the end users. With the 'Human-in-the-loop' approach more than 20% energy savings can be achieved on heating demand and up to 40% energy savings on cooling demand compared with the actual energy demand.

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WIRELESS SENSOR TECHNOLOGY TO OPTIMIZE THE OCCUPANT'S DYNAMIC DEMAND PATTERN WITHIN THE BUILDING

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ABSTRACT

Energy needs to be used as effectively as possible by anticipating on the human behaviour with the purpose of providing optimal comfort. The purpose of this research is to assess the energy saving potential by sending the energy to those spots (hotspots) where needed and to determine how the user can be taken into account in the design to improve the performances of office buildings. Possibilities for human position tracking measurements by means of a WSN were investigated to determine the user behavior of aoocpants of a building. An experimental set-up was developed which was implemented on the 3th floor of one of the offices of Royal Haskoning consulting engineers. This showed the positive effect of using wireless technology to optimize the occupants comfort while minimizing the energy consumption,

INTRODUCTION

As until now in practice user behaviour has not been part of the building comfort system control strategy in offices, the energy consequences of the user behaviour are not accounted for. However, occupant presence and behaviour has a large impact on space heating, cooling and ventilation demand, energy consumption of lighting and room appliances (Page et al. 2007) and thus on the energy performance of a building (Hoes et al. 2009). User behaviour may be defined as the presence of people in the building, but also as the actions users take to influence the indoor environment, the opening or closing of windows or blinds. Human behaviour can be explained to result from physical needs and psychological needs (Tabak and de Vries 2010). Physical needs are highly individual and concern space, light, climate conditions and sound (Zimmerman 2006). The psychological needs are the result of interaction, privacy and personalization, so obviously highly individual too. Human behaviour related to the physical conditions can be described in terms of user control of the installation systems and building facilities like windows. In this context user behaviour may be defined as the presence of people in a workplace location in the building and the action users take (or does not take) to influence their indoor environment (Hoes et al. 2009). Recently models have been developed to describe human behaviour and include it in building performance analyses (Degelman 1999, Nicol 2001, Reinhart 2004, Bourgeois et al. 2006, Mahdavi 2006, Rijal et al. 2007, Page et al. 2007, Hoes et al 2009, Tabak and de Vries 2010). However, only a few studies successfully demonstrated energy reduction from occupancy behavioural patterns that had been determined because there was no formal connection to the building energy management systems of these buildings (Dong and Andrews 2009). The main research fields of user behaviour in office buildings were occupancy models and occupant control on shading device, window, artificial lighting, appliances and thermal environment. Several occupancy models have been made, but they are hard or even insufficient to apply, because they were targeted at specific buildings.

When the occupancy of the building can be predicted, major profits can be gained with regard to energy usage. In addition, users are shown to consistently over-turn actions in response to uncomfortable conditions, causing oscillations that can waste energy and create an uncomfortable environment. Especially for lighting and shading control, incorporating user behaviour in advanced control algorithms shows high potential to significantly reduce the building energy loads. However, as until now user behaviour were not part of the building comfort system control strategy in offices. As there is not many specific research on the effect of user behaviour in office buildings, first a user-actions analysis was performed in cooperation with Royal Haskoning, one of the major Dutch HVAC engineering consulting companies.

FIRST ANALYSIS OF HUMAN BEHAVIOUR ON ENERGY CONSUMPTION

The 3th floor of one of their office was chosen as it is a characteristic and representative example of their office working situation. Fig. 1 shows the floor of the building and Fig. 2 illustrates the parameters which might have an influence on the personal actions.

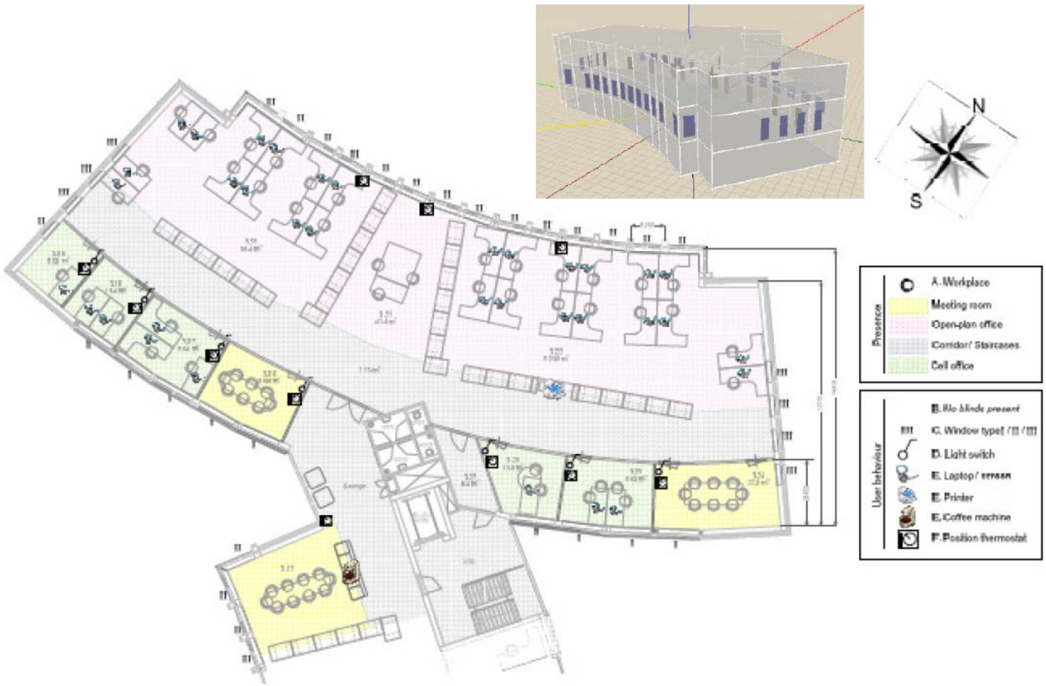
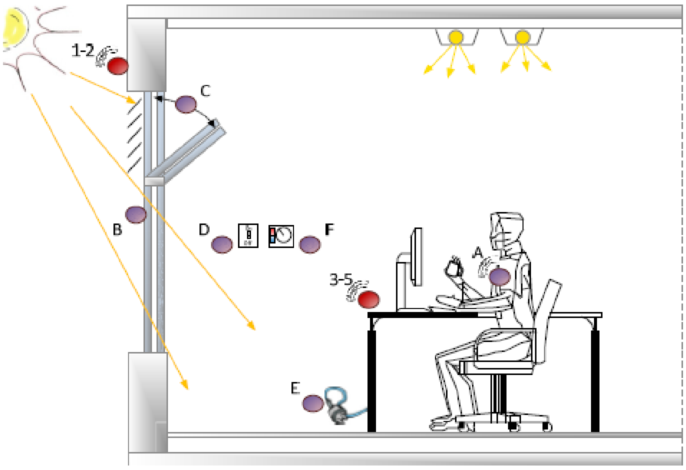


Figure 1 Test case 3th floor of an existing office building



Sensor Nr.	*Measured value*
	External
1.	Temperature
2.	Illuminance
	Internal
3.	Temperature
4.	Illuminance
5.	CO_2 level
A.	Occupancy / presence

Figure 2 Personal actions and parameters in an example office

For the calculation of the effects of the user behaviour on the energy consumption of the building, the latest version of the VABI (Vereniging voor Automatisering Bouw en Installaties, Society for automatization in Building Industry and Building Services) Elements heat/cooling load calculation tool was used. VABI is the most important Dutch software developer of software calculation tools for building systems, with emphasis on Heating Ventilation and Air Conditionings systems, thermal aspects, electricity and solar energy. The 3th floor of the case study office was modeled in the VABI elements model, this made it possible to calculate the effects caused by actions of the occupants. The input parameters were based on observations of the occupants' behavioural actions during a week. To test the sensitivity of the process outcome, in relation to specific user actions, input parameters were changed within an acceptable and realistic bandwidth based on the observations. The output results from the VABI model for the office space 3.20 – 3.22 are shown in Fig. 3 and represent the total sum of the heating and cooling demand for a year. A high bandwidth means that the parameter is a critical performance indicator in relation to the occupants' behaviour, as it has a major impact on building performance.

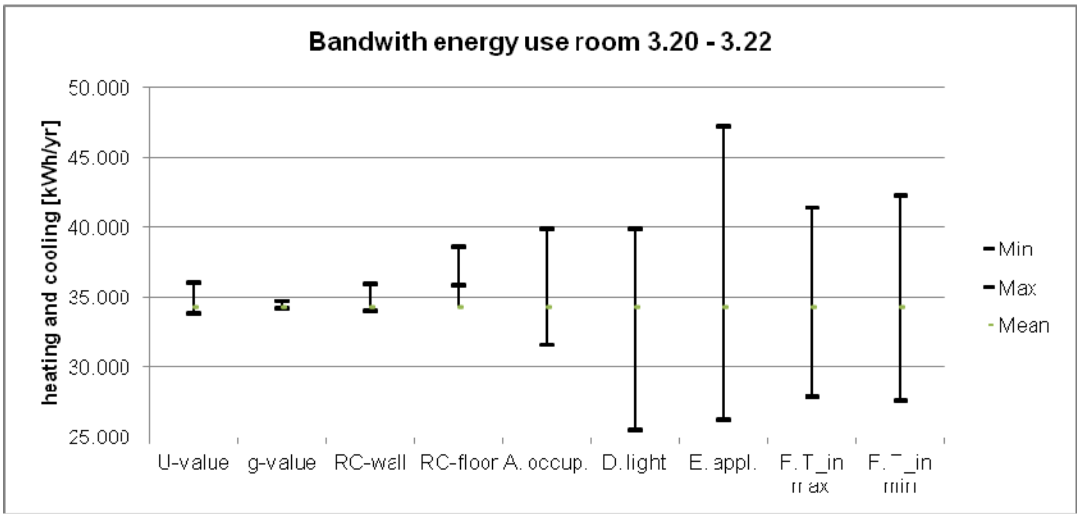


Figure 3 Bandwith of results from VABI elements for the total energy demand of room 3.20 – 3.22 as caused by changing the specific input parameter

Based on the above figures it was concluded that some of the parameters (occupancy, lighting, electrical appliances and temperature setting) related to user behaviour have a clear and high influence (up to plus or minus 30%) on building performance. This underlines the importance for focusing on the inclusion of human behaviour for improving building process control performances.

ANALYSIS OF OCCUPANTs' MOVEMENTS WITHIN THE BUILDING

The idea is that when the actual need for comfort of the individual building user is addressed, this will lead to reduction of the energy consumption by the building systems. Thereby, the control objective is to look how the individual building occupants' movements, their staying on different locations within their building.

Distributed information can be obtained by low-cost wireless sensor networks (Arens et al. 2005, Tse and Chan 2008), low-cost infrared sensors (Buydens 2006) (Revel and Sabattini 2010), and smart badges/portable nodes (Feldmeier and Paradiso 2010). This distributed information could provide insights in the ongoing processes on different levels (personal-, local-, and room level) which can be used for user-adaptive comfort control. Wireless sensor networks become more popular for application in climate control (Neudecker 2010, Gameiro et al. 2010, Kim et al 2010, Yu et al. 2011, Rawi and Al-Anbuky 2011, Jiang et al 2011, Georgievski et al. 2011, Park 2011). Still there is a huge gap to practice as there is at the moment only one company which offers WSN for climate control in the Netherlands and has only realized a few projects in the last years (Octalix 2011). It is necessary to come with new application of WSN, therefore a close look was needed into possible additional functionality of WSN in regards to human behaviour.

Arens (Arens et al. 2005) proposed a distributed sensor network for office rooms. At room scale, the control and actuation could take place within the room itself by a kind of remote controller. The persons' thermal state (comfort state) could be predicted from measured skin temperatures sensed through contact or remotely by infrared sensors. In the proposed concept user behaviour was taken into account by an occupancy sensor. Feldmeier and Paradiso (2010) developed a personalized HVAC system consisting of four main components: portable nodes, room nodes, control nodes, and a central network hub. At the heart of the system was the building occupant; this was where the comfort information resided. To best assess the occupants' comfort level, a portable node was developed which senses the local temperature, humidity, light level, and inertial activity level of the user. It also the system interface had three buttons on the side, which allowed the user to input current comfort state (one button each for hot, cold, and neutral). The actuation of the various heating and cooling systems was achieved via control nodes. Energy savings of up to 24% over the standard HVAC control system were achieved during experiments on MIT University (Arens et al. 2005).

Applying the bottom-up approach, with the human in the control loop of building services systems, could only be achieved if users could be located within the building. Low-budget wireless sensor networks with portable nodes show high potential for real-time localization and monitoring of building occupants (Feldmeier and Paradiso 2010). Therefore static wireless sensor nodes were mounted on the floor and communicate with mobile nodes (or in the future smart phones) carried by the occupant to determine the position of the occupant on workplace level. The measurement set-up is schematically shown in Fig. 4.

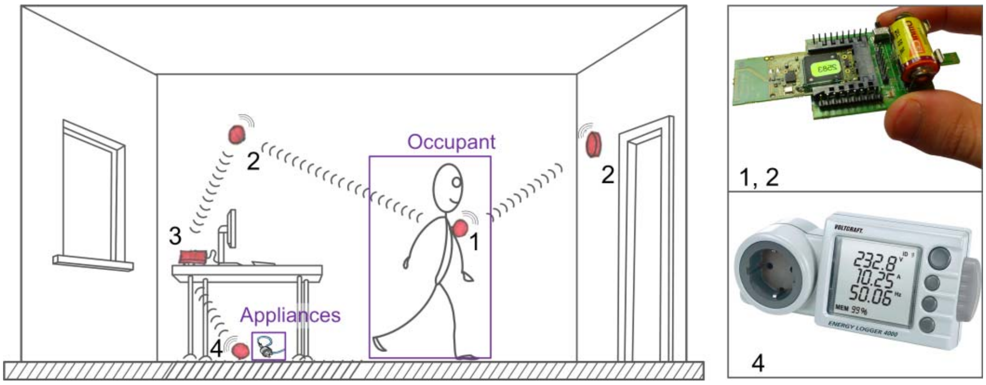


Figure 4 A wireless sensor network (2) tracks the mobile node (1) of the occupant and the energy use of appliances (4) and uses the real-time data for the building system control (3)

The wireless static nodes for position tracking of the occupants were placed on points of interest e.g. the workplaces, printer, coffee machine and toilet. Based on the signal strength the nodes locate in which zone the occupant is. With the nodes a mesh was created consisting of 30 zones. Fig. 5 shows that there was a more refined grid around the workplaces than, for example, in the corridors. In every zone one power logger was installed, for measuring the energy use and to get an estimation of the heat production.

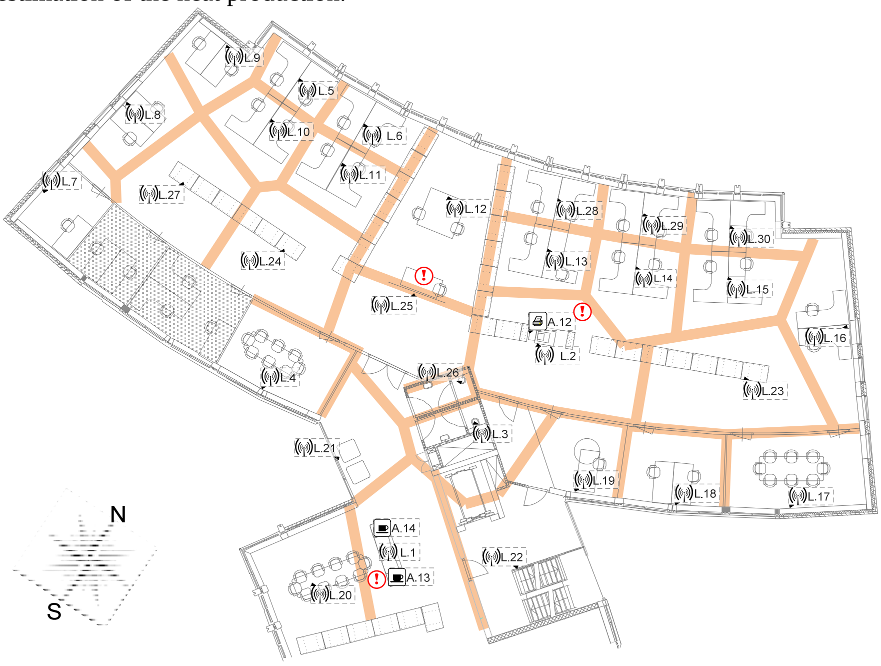


Figure 5. Positions of the static nodes creating a mesh of the zones for measuring the position of the building occupants on the floor. The transition region between the zones is marked by the broad orange line

RESULTS

Determination user comfort and energy saving potential

A model was built to determine the primary heating and cooling energy demand for four different cases: energy demand as designed (A), actual energy demand (B) and when taking the 'Human-in-the-loop' on room (C) and workplace level (D). The simulation was performed using a whole building model programmed in the Simulink HAMBase environment. In contrary to earlier research by (Zhang et al. 2009), this study takes into account the real occupancy profiles, the appliances use, lighting profiles and the energy needed for personalized conditioning of the occupants.

In the four cases the building parameters were the same, only there was a change in the user profiles. These user profiles input variables are explained in more detail.

A. Design input

In the design phase assumptions were made for the different user influences on building performances. The zones of the building model were equal to the rooms of the floor plan. The values are shown in Table 1.

Table 1 Overview of the input values for the building simulation on workdays

Simulation input	A. Design	B. Actual	C. Room	D. Workplace
A. Metabolism	10 W/m^2 8-18hr	1.1 Met/prs Occ./room*	1.1 Met/prs Occ./room*	1.1 Met/prs Occ./zone*
D. Lighting	10 W/m^2 8-18hr	Power/room* 8-20hr	Power/room* 8-20hr	Power/zone* 8-20hr
E. Appliances	10 W/m^2 8-18hr	Power/room* -	Power/room* -	Power/zone* -
F. Temp. (heating) Night	22 (8-18hr) 19	Temp./room* Temp./room*	If occ. 22 else 19.5 18	19.5 with pers. heat. 18
F. Temp. (cooling) Night	24 (8-18hr) 25	23.5 (8-18hr) 25	If occ. 23.5 else 25 25	If occ. 23.5 else 25 25

* Indicating the application of measured profiles from the case study measurements

B. Actual energy demand

For the simulation of the actual energy demand all measured profiles were applied. The occupancy contributed to both sensible and latent heat load in the room. The activity level of the occupants was assessed at 1.1met (1met=58.2W/m2, Ad=1.8m2), which is standard for office activities such as typing. For the heating the measured temperature profiles were used as temperature set point. In the winter a temperature set point of 23.5 °C during working time was assumed.

C. 'Human-in-the-loop' – room level

Here only the temperature set point was changed compared to the actual energy demand. When the room was not occupied a bigger bandwidth for the room temperature was allowed in both the winter and summer situation.

In Fig. 9, the measured profiles for occupancy and appliances are shown for a typical reference day in the open plan office. The occupancy is presented as a fraction of the full occupancy. During the day the maximum occupancy equaled 80%. For the appliances, the total heat load is presented in Fig. 6. Remarkable to mention is that even when the occupancy strongly decreases (e.g. during the lunch break at 12.00h), the heat load by appliances did not significantly change.

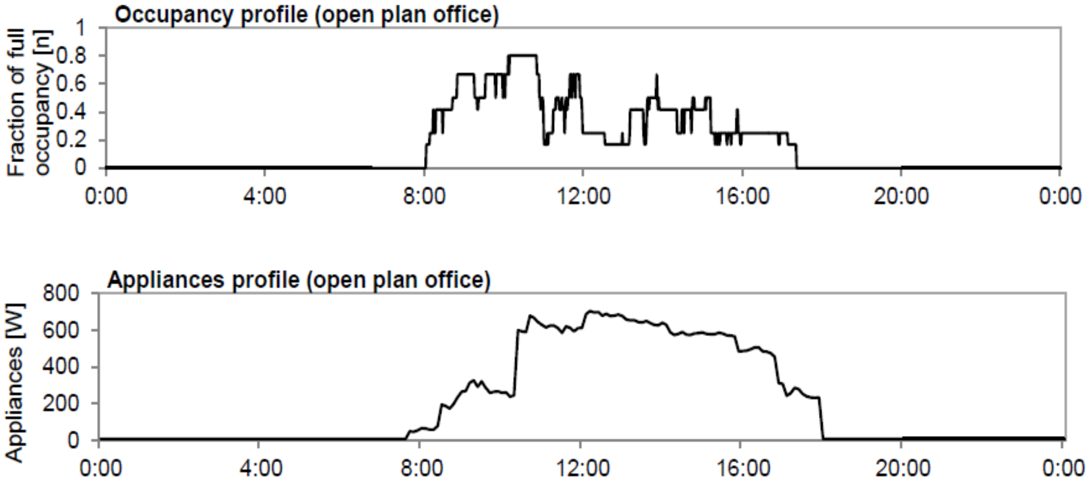


Figure 6 Measured profiles for occupancy and appliances for a typical winter day

D. 'Human-in-the-loop' – workplace level

In this case the model was divided into the 30 zones, which were the same as the conducted measurements on the case study floor. The internal heat gains of metabolism, lighting and appliance use were now applied on the zone level. From recent research (Vissers 2012) it was concluded that by controlling the finger temperature in a small bandwidth the overall thermal sensation was maintained at neutral or slightly higher, while an indoor air temperature of 19.5ºC was applied. Therefore hand heaters with a power with a total power of 98W were applied. Since no obvious results could be found for personal cooling, a comfortable temperature set point of 23.5 °C is assumed when a zone is occupied. The change of set point was only applied on the workplaces, e.g. no hand heaters were applied in the toilet or nearby the location of the printer or coffee machine.

Simulation model

A simplified sketch of the simulation model in Simulink is shown in Fig. 7, in this case D. control on workplace level with 30 zones. In simulation A, B and C the zones of the model corresponded to the physical rooms in the building.

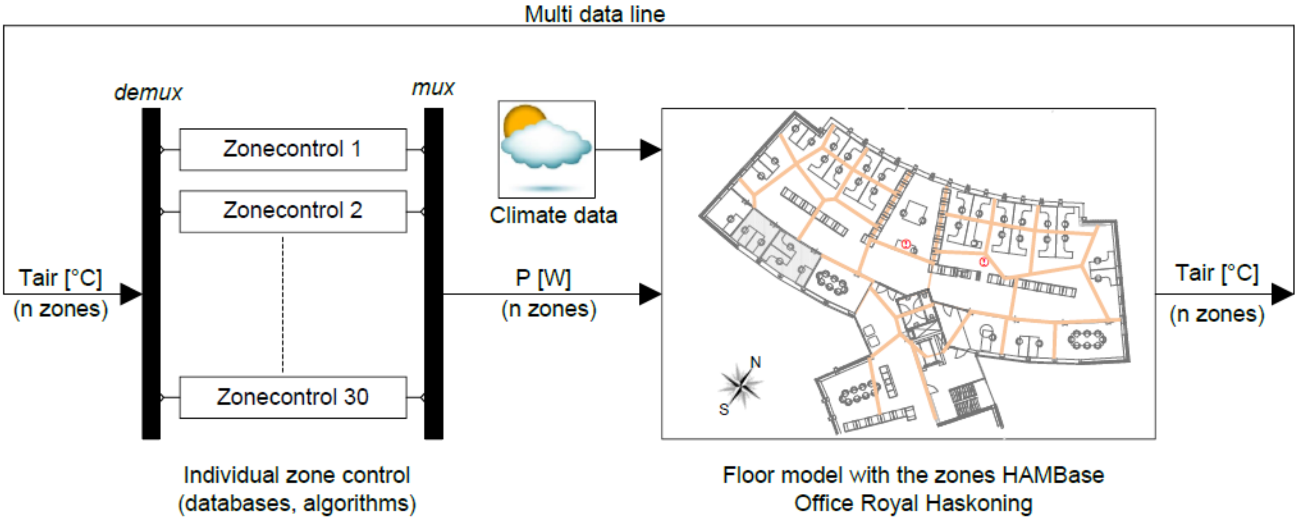


Figure 7 Simplified sketch of the simulation model in Matlab/Simulink. The air temperature was used as feedback control signal for the individual zone models.

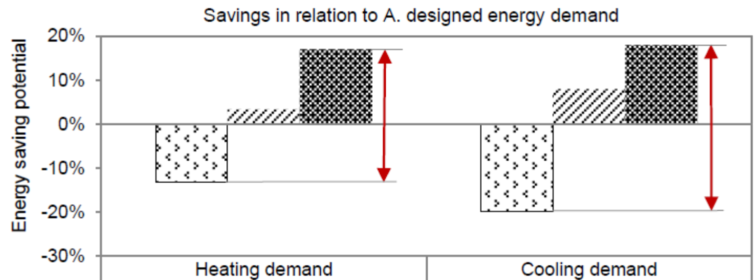
Climate data of the measured 6-week winter period was coupled to the whole-building model. The indoor air temperature of the zones was the output of the whole-building model. This information was used as feedback signal for the control algorithms of the individual zones. A demultiplexer (demux) was used for selecting the data-output from this feedback signal. A multiplexer (mux) was used for combining several data lines into one single signal line. About the simulation model the following can be said:

- Each zone has its own control loop for regulating the indoor air temperature (Fig. 7).
- For the basic room heating (Pbasic) a proportional control algorithm is applied;
- In the cased C and D only control of the temperature is changed, meaning that ventilation rates are not changed according to the occupancy. It is highly potential that the energy demand will drop significantly when this is applied.

Energy

The (primary) energy saving potential was calculated according to equation 1. The energy needed for the case was divided by the energy needed for the reference situation which was the design situation. The results are presented in Fig. 8.

$$\text{energy saving} = 1 - \frac{(Q_{\text{basic}} + (\sum Q_{\text{local}}))_{case}}{(Q_{\text{design}})_{@22ºC}} \qquad (1)$$



	Heating demand	Cooling demand
B. Actual energy demand	-13%	-20%
C. Human in the loop - room level	3%	8%
D. Human in the loop - workplace level	17%	18%

Figure 8 Energy saving potential for heating and cooling calculated for a 6-week period, compared with the designed energy use. The energy saving potential of the people-oriented energy control on workplace level compared to the actual energy demand is indicated with the red arrows.

From this figure it was concluded that an increase occurs in energy demand for both the heating (13%) and cooling (20%) in the actual situation. When applying people oriented control on room level, energy savings could be obtained compared to the design reference situation. A higher energy reduction was obtained when the temperature was controlled on workplace level applying personal heating and cooling. Compared to the actual energy demand an energy saving close to 30% for heating and up to 45% for heating could be obtained.

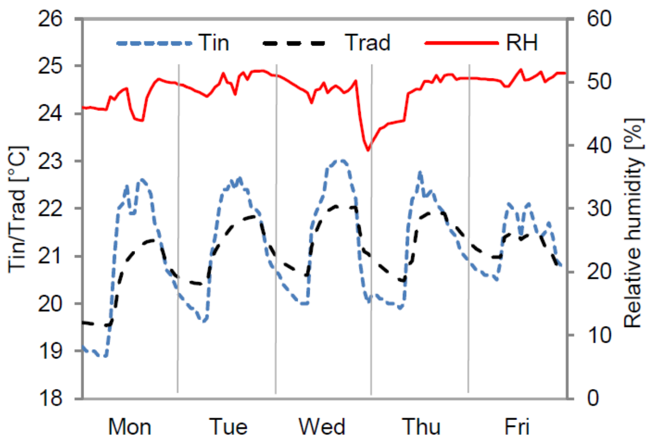
Comfort

Occupant comfort for the cases B. actual situation and C. control on room level were compared with the designed thermal comfort based on the PMV value. Since there was no model available looking at the individual comfort, the well-known PMV index was used. From the measurements the temperatures were available, the averaged radiant temperature and relative humidity were calculated by the building simulation. For the purpose of this evaluation, all other PMV values were considered to have the fixed values shown in Table 2.

Table 2 Fixed parameter values for PMV calculations

Parameter	Clothing (Clo)	Air velocity	Metabolic rate	External work
Value	1	0.1 m/s	1.2 [W/m^2]	0 [W/m^2]

The PMV values were calculated for the third week in January 2012. The applied indoor temperature, radiant temperature and relative humidity parameters for the PMV of the actual situation are shown in Figure 9. The room temperature fluctuated during the day around three degrees Celsius and the radiant temperature circa two degrees Celsius. The relative humidity was between 40% and 50% during this working week. The results of the PMV calculations are shown in Figure 10. The green area presents the designed values between which the PMV should be. In the actual situation, the PMV value did not meet the designed value for 25% of the time. This could be explained by a wrong operation time of the HVAC system, where the building was not yet at its desired temperature at 8 AM. For case C the room temperature set point was 19.5°C when no one is present in the room. The PMV values were only counted for when someone was present. It was clearly visible that the PMV value was lower, where 50% of the values were below the comfort boundary. However, this PMV did not take into account the time it took (5 - 10 minutes) before a building user perceived the change in temperature in slightly cool environments (Wang et al., 2007).



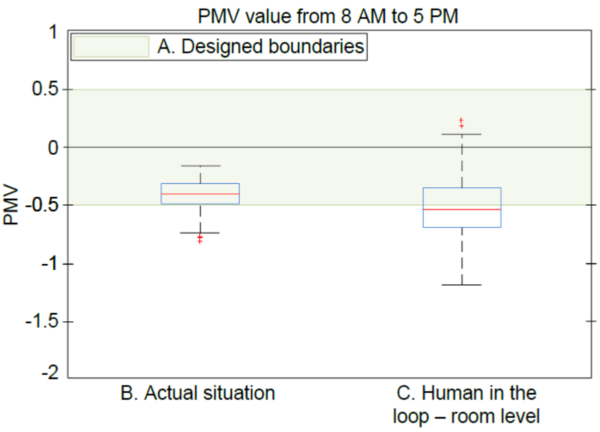


Figure 9 Applied room temperature, radiation temperature and relative humidity to the PMV model, from the third week in January 2012 and Figure 10 PMV designed boundaries compared to PMV result of: B. actual situation and C. applying energy on room level where the values are based the simulation results. Calculated for one winter week between 8 AM and 5 PM

In his research Vissers (Vissers, 2012) showed that it was possible to feed-forward respond to user thermal preferences (i.e. before cool discomfort occurred), while the basic room air temperature was 19.5 °C. By conditioning the hands with a radiation panel the local- and overall thermal sensation of tested subjects were maintained neutral or slightly higher level. Therefore it was assumed that the PMV was between the boundaries when applying local heating. The application of local heating and cooling shows high potential, especially when combining it with the possibilities of indoor localization. The (primary) energy saving potential for heating was calculated according to equation 2. The energy needed for the case was divided by the energy needed for the reference design situation. The results are presented in Figure 11.

$$\text{energy saving} = 1 - \frac{(Q_{\text{basic}} + \sum Q_{\text{local}})_{case}}{(Q_{\text{basic}})_{@22^{\circ}C}} \qquad (2)$$

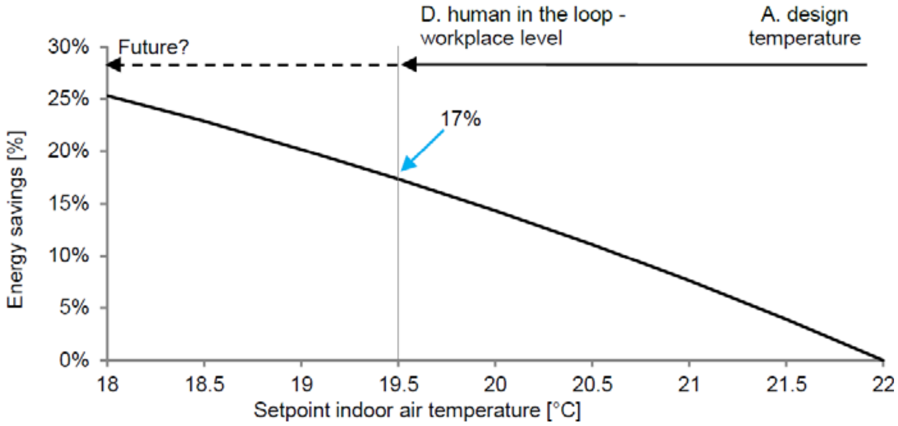


Figure 11 Energy saving potential for heating energy calculated for a 6-week winter period, by decreasing the indoor air temperature set-points and applying local heating per occupant. In the reference case the indoor temperature is controlled at 22ºC without local heating.

The energy saving potential for heating is 17%, as shown in the previous section, when lowering the set point of the indoor air temperature from 22ºC to 19.5ºC and taking into account personalized heating of 98W per occupant (Vissers 2012)

DISCUSSION

Simulation results compared to literature

It was important to verify our simulation results. Zhang also reported the potential energy savings, obtained by a numerical study, for different climate zones in the United States, by expanding the dead-band of the process control setting in which the room temperature is controlled (Zhang et al. 2010). The energy use of a necessary local task-ambient conditioning (TAC) system to still make it comfortable for the occupants was not taken into account by Zhang. Therefore the energy savings, as found in our research, are less high compared to those of Zhang for a similar climate zone, around 23% (Zhang et al. 2009). In addition Van Oeffelen simulated the energy potential for a typical winter situation in the Netherlands. They calculated an energy saving potential of about 25% for heating by decreasing the room temperature set point from 22ºC to 20ºC (Oeffelen et al. 2010), which is about 8% higher as found in this research. However, our research considered real occupancy profiles and real energy use for individual local heating, which makes the results more realistic.

One of the limitations of the current research is the focus on individual workplace, were as in practice there are often shared workplaces. The problem of shared spaces is inherently very tough to solve, because all individual preferences and differences cannot be matched. One strategy in these settings could be to try to minimize the level of comfort conflicts within the group of shared working places.

The use of electrical appliances is the most influencing variable on building performance, see Fig. 3. In previous research Parys concluded that the operation of office equipment is obviously not driven by indoor environmental quality motives. Therefore it is more logical to link the ratio of internal heat gains over the nominal power of office equipment to the occupancy rate (Parys et al. 2011)
When the averaged profiles for occupancy and use of electrical appliances are looked into, there is a strong correlation between them with a determination coefficient of 0.94. Looking at workplace level there is no clear correlation. This is proven by Fig. 12 with the occupancy and appliance use for two reference days. Connections were visible, but the appliance use did not correlate with the occupancy.

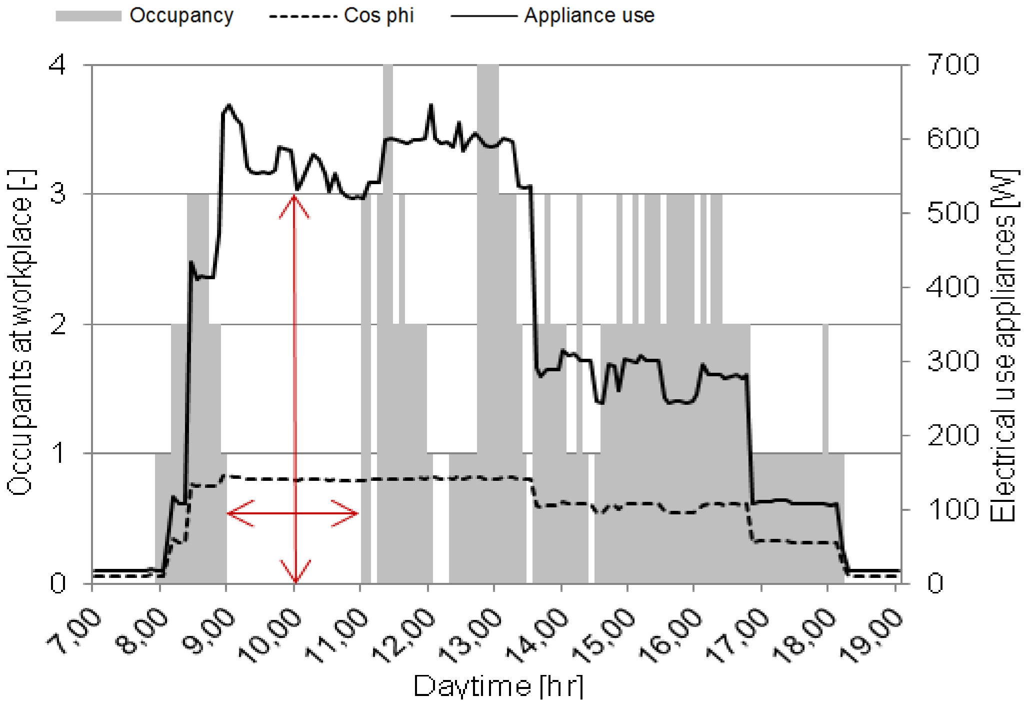


Figure 12 Occupancy for 4 workplaces and total energy demand for those places for a reference day, time step = 5 minutes. The red arrows indicate that energy demand can be reduced when the occupants are not at their workplace.

'Human-in-the-loop'

This 'Human-in-the-loop' approach is able to locate the user position, so energy can be applied to the spots where there is a demand of the building user with his individual comfort. This does not mean that control devices, operable windows, and other adaptive user actions on room or workplace level are superfluous. As the study by Hoes (Hoes et al., 2009) showed, the ability for a person to control his environment has a significant impact on occupant satisfaction. This asks for a system which combines (i) localizing the building occupant and automatic conditioning of his workplace, and (ii) the possibilities for adjustments of the users' environment. To apply the individual preferences on the workplace, the human should be included in the loop through controlling his individual comfort level to prevent discomfort and energy consuming behaviour of the occupant to restore his comfort level.

Measurements

The measurements on the case study floor only took place for a period of six weeks in winter period. Firstly this means that the obtained results may only be accounted to this measurement period and secondly they are only valid for this case study floor. Mahdavi (Mahdavi et al., 2009) already described that results from one building cannot be transposed without extensive calibration measures, considering differences in buildings use.

During the measurements not all building users wore a node. Therefore it is plausible that an error in the results consists since the appliances of all the users are measured. Since almost 80% of the floor users wore a node the error might be kept at a minimal.

CONCLUSIONS

User behaviour can be defined as the presence of people in a workplace location and the action users take (or do not take) to influence their indoor environment. However, interactions with the buildings' environmental systems are difficult to predict at the level of an individual person. In general, building occupants interact with a building to enhance their personal comfort (e.g. by heating or cooling their local environment to improve their thermal comfort or adjust lighting system or blinds to optimize their visual comfort etc).

With increasing energy performances, the influence of the occupant becomes significant and should be looked into. In the used case study the human influence is 3-5 times higher than variations in building parameters. With the 'Human-in-the-loop' approach energy is only sent to those spots where needed by localizing the building occupant and anticipating on its influences. From measurements of 20 employees during 6 weeks on an office floor it is clear that individual occupancy can be distinguished. A strong correlation between the occupancy and the most important human influence on building performances, use of electrical appliances, was shown on floor level. However, on workplace level a relation between occuoancy and use of electrical appliances is not clear. Further research towards possibilities and advantages is needed.

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Designing Zero Energy Building for Tehran

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1. Abstract

In this paper, design of a zero energy building (ZEB), a case study for Tehran, in a moderately warm climate, for a typical single family has been introduced. It is important to develop solar energy resource potential in order to use it in construction of enhanced buildings. The benefits including reducing fossil fuel consumption, fading energy supply cost and lowering environmental pollutants, have created a growing tendency to these types of buildings. Calculating solar energy radiation and the house load are the basic steps to design a ZEB. Following steps are designing the heating, cooling and domestic hot water (DHW) systems and providing the electricity for appliances and lighting and designing the storage system. Economical features and environmental issues make ZEBs an appropriate solution for emerged problems of common houses and thus investments in large (state-wide) scales may be justified.

Keywords: Case Study for Tehran, Economical Features, Environmental Issues, Solar Energy, Zero Energy Building

2. Introduction

Energy is one of the most interesting topics for scientists to explore. Improving efficiency of energy consumption in buildings is a response to increased energy costs and lack of energy supplies. ZEB is one of the solutions to decrease greenhouse effect.

A zero energy building refers to a building with net zero energy consumption over a typical year. Such buildings can be dependent or independent on the electrical grid. A grid disconnected ZEB is difficult to implement, both from an economical and technical point of view due to the seasonal mismatch between energy demand and renewable energy supply. So approaching a Net ZEB (NZEB) is necessary: A grid connected ZEB does not require on site electrical energy storage, any surplus in electricity production is injected into the grid, conversely, when production is insufficient, the building draws from the grid.

The goal which is followed in this case study paper is not only to minimize the energy consumption of the building with passive design methods, but also to design a building that balances energy requirements with active techniques and renewable technologies (for example, solar photovoltaic panels and solar thermal). The further goal is to approach a zero energy building which does not need any input even though it can export electrical power to the grid when it has excess power generation. Another goal in this design is to the reduce carbon dioxide emissions in order to help scientists and environmental experts who are trying to find advanced technologies to diminish carbon dioxide emission.

In this 100 square meter home, solar energy is the main supply which provides thermal comfort, hot water and electricity needs, using combination of collectors and photovoltaic panels. Special insulations as a construction technique used in passive design cooperated with blind shading resulted in our goal, a super insulated home! HVAC requirement is met by both passive and active approaches with respect to moderately warm climate in Tehran. An absorption chiller as an active system has been utilized to support both heating and cooling. This system absorbs solar energy by making use of an optimized combination of flat-plate and evacuated collectors. And domestic hot water demand (DHW) is also supplied in part of our main absorption cycle to reduce the size of the equipment and consequently decrease the costs. In case of inadequate radiation, auxiliary system contributes the main system to meet the demands of this home. Several batteries are used to save extra energy from PV cells during the day for necessary conditions like night-time or cloudy days. To decrease energy consumption, LEDs and fiber optics used in lighting system. Fiber optics can transmit natural sunlight to the inner spaces of the house. Off-grid solar photovoltaic system has been chosen for energy storage. Stored energy utilized in appliances, lighting, HVAC auxiliary system and controllers. Biogas as an auxiliary system has been used to prevent usage from the stored energy in batteries.

The study presented in this paper, traces the following steps:

1. Describing the passive strategies used in the house.

2. Calculating maximum heating and cooling load for Tehran

3. Exploring the solar radiation data

4. Predict energy demand profiles:

    a. Thermal energy for ambient heating and cooling.

    b. Thermal energy for domestic hot water (DHW).

    c. Electrical energy needs for lighting and appliances.

5. Designing an active system for heating and cooling and domestic hot water (DHW).

6. Perform the lighting and energy storage system.

3. Passive Strategies

To use solar energy in natural lighting and thermal comfort, passive design strategies have key roles. Shading and thermal mass are also used to obtain the optimum solar energy.

To gain the maximum solar energy many different methods are available, three of which are used in this study:

a. Direct gain. In this method, large glazed south-facing windows are used in order to gain the direct solar energy for natural lighting and thermal needs. Large amount of glazed south-facing windows can cause overheating. In this house, shading and thermal mass which are used in dining room and kitchen maintain the home from overheating. The area of south-facing window is about 9 percent of floor area. In addition, the windows used in other sides of the house have the minimum area.
b. Indirect gain. Trombe-wall which is used in the larger bedroom provides more than 40 percent of heating load required for this zone. In winter time, when the air located in the upper vent is nearer to the comfort condition more than room air, the vent would open and the air is circulated in the room until it reaches the comfort condition. Then, the vents would become closed again.
c. Isolated gain. In order to save the energy, there is a glazed room which is located at home entrance.

The orientation of different parts of home is based on passive design in order to use the day light and solar thermal energy. The kitchen, dining room and larger bedroom are located on the southern side of home and living room and the other bedroom are located on the northern side.

All the windows are shaded by different types of shadings based on their location. For example, all south-facing windows are shaded by roller-shading. An important goal followed in passive design is reduction in energy loss of home. This is where insulation plays a vital role. Creating super insulation conditions is followed in this project strongly by choosing materials with low overall heat transfer coefficient.

4. Architecture

This study builds on a $96m^2$ ($12^m \times 8^m$), single-story house with two bedrooms. The plan of the house is shown in figure below. Table 1 show the construction material used in the house. The U-value of building elements are indicated in Table 2.

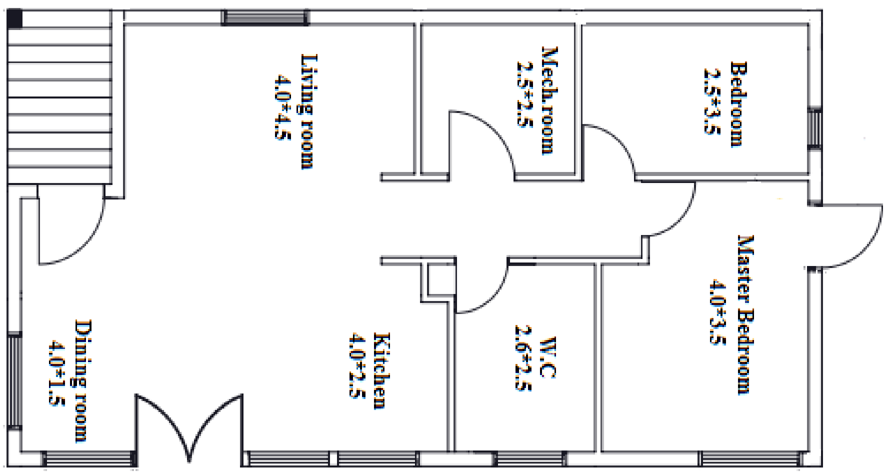

Fig.1. House plan

Table 1: Building construction materials

Building elements	Materials
External walls	Concrete block and brick
Glazing	Double insulating glass (suspended film and low-E)
Internal partitions	Plasterboard and insulation
Roof construction	Concrete tiles, felt/underlay
Doors	Metal Insulating (2” w/urethane)

Table 2: U-Value of different parts of house

Building elements	U-Values ($Btu/ft^2.hr.$°F)
Exterior walls	0.02
Interior walls	0.038
Outside doors	0.067
Room doors	0.27
Glasses	0.247
Room ceiling	0.015
Tilted roof of bedrooms	0.083
Tilted roof of living room	0.015

5. Heating and Cooling and Hot Water Demand

In order to maintain thermal comfort for the house residents, several factors including temperature and humidity should be controlled to stay at a certain level. The designed system not only does meet these demands, but also supply the hot water need of the house. In this section, required steps for mentioned design are expressed.

5.1. Operating Cycle

In the case of zero energy buildings, space heating and cooling systems may run on either electricity produced by PVs or solar thermal energy absorbed by collectors. A comparative estimation of capital costs based on load peaks for a solar absorption chiller and a compression heat pump indicates the value of 30000$ for the former and 36000$ for the latter. Furthermore, environmental issues and intangible costs lead us to choose the absorption unit as mechanical system. The designed absorption heat pump has the capability of supplying heating and hot water demand as well as cooling; thus, this system contains collectors, storage, and auxiliary energy system as shown in Fig. 2.

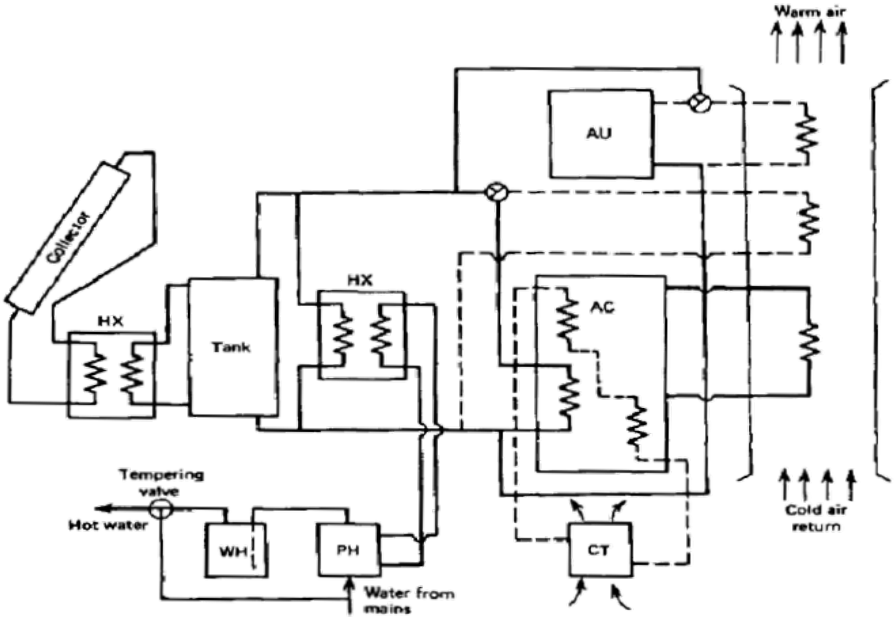

Fig.2. Schematic view of operating cycle

5.2. Hot water

In order to determine the amount of hot water which is required in a day, the data from engineering handbooks have been used and the demand rate calculated for a family with 4 members in Tehran is 233 gallons per hour, which leads to 0.00377 kilograms per second per day. The energy demand profile is obtained for Tehran according to the calculated hourly hot water use, as is presented in the red line of Fig. 5.

Mechanical system and its components are shown in Fig. 3. The DHW cycle is designed in a way that during day light, the cold supply enters the solar tank, becomes hot, returns to the storage tank and exits the path to supply daily need. In contrast, at nights, cold supply is led directly to the storage tank, gets warm and exits from the cycle to provide the house with its needs.

A specific characteristic of the designed system is the use of tempering valve which enables us to stratify the exit water according to its temperature. In the cases water with less temperature is needed, tempering valve in open to reduce the temperature.

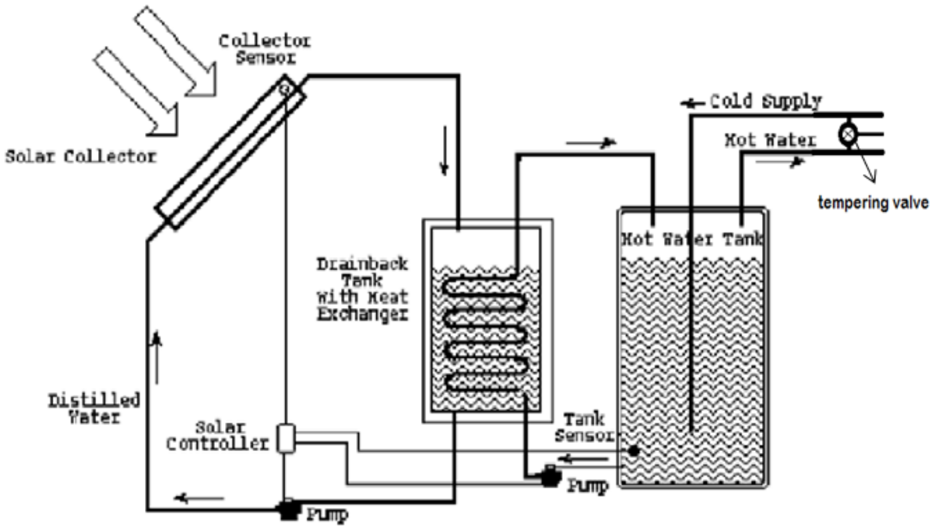

Fig.3. DHW system

5.3. Design of Solar Thermal Power System

Heating and cooling demands of a detached residential house should be met with respect to some important criteria such as human comfort and regional climatic conditions which mainly impose some limitations on the design process. So as the first step, hourly total solar radiation on the tilted surface is calculated. The results shown in Fig. 4 represent the effect of the surface orientation.

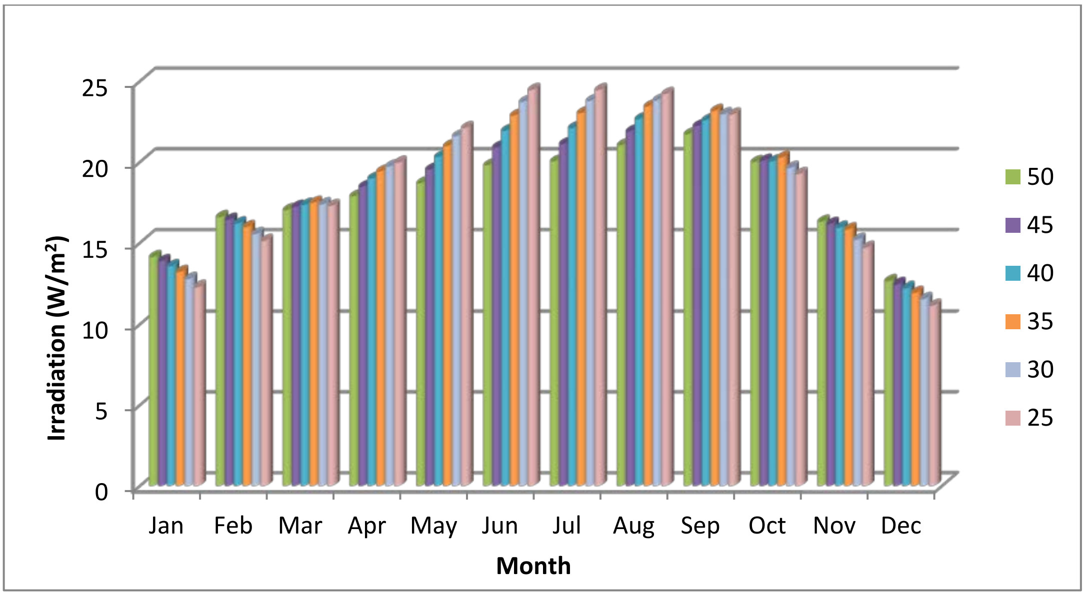

Fig.4. Incident radiation for some slopes

Using mechanical lever enables us to alter the collector orientation each month and achieve the maximum input; however, in order to obtain a safe design, following calculations are conducted based on the slope of $30°$ for collectors.

In this typical home in Tehran, concept of utilizability has been used. Utilizability is defined as a radiation statistic that represents the fraction of the total radiation which is received at an intensity higher than a critical level. As a result, total utilizable energy in Tehran is calculated in order to assign the absorption chiller capacity and type of the collectors. It is important to note that the design procedure in this way is quite iterative since the absorbed and utilizable energy depend on the collector type and characteristics; however, the collector itself is selected according to evaluated demand and incident irradiation.

Table 3 summarizes the results for the calculated monthly average hourly utilizable energy in the daylight hours for Tehran which represents a cold and a warm month. Note that the data is symmetrical after the solar noon.

Table 3: Utilizable energy in daylight hours

	6-7	**7-8**	**8-9**	**9-10**	**10-11**	**11-12**
January	0	0.2649	0.7041	0.7959	0.8317	0.8456
July	0.6348	0.7553	0.8096	0.8382	0.8536	0.8604

With assumed collector characteristics, useful gain per unit surface area is calculated. These values in conjunction with heat pump coefficient of performance (COP) constitute the available energy which should satisfy cooling and heating loads during the year. Monthly energy demand for space heating and cooling is obtained by curve fitting according to total annual heating and cooling load and measured load peak. Note that the heating load is calculated in a day in January with ambient temperature of $-4℃$ and comfort temperature of $24.5℃$ and cooling load is also calculated in a day in July with ambient temperature of $36.6℃$ and comfort temperature of $25.5℃$. The achieved results are $1.5ton$ for heating and $1.8ton$ for cooling. Furthermore it should be mentioned that total annual space heating load is $0.824GJ$ and annual cooling load is $1.008GJ$ and in order to obtain the hourly demand profile, the curve fitting is carried out in concern with the assumption of negligible load in March and October.

Fig. 5 shows the results for three different collector surface areas. The available energy from collectors is a design parameter which has to meet the average demand for all of months.

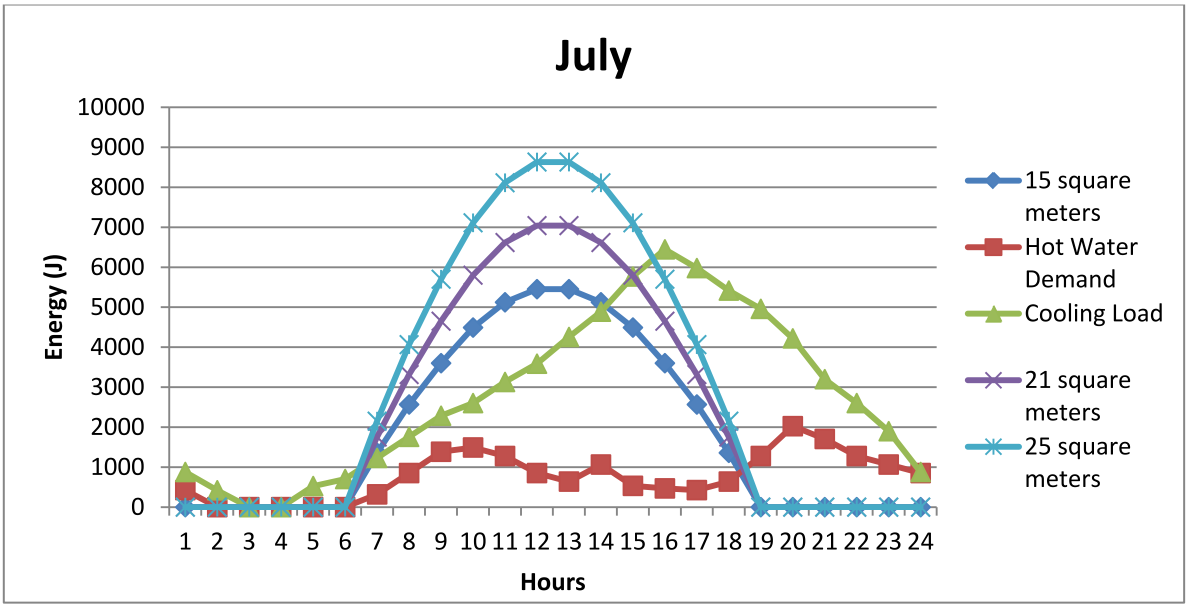

Fig.5. Useful Energy for three surface area and needs

Note that the auxiliary system using PV cells compensates the shortage during one day. Comparing the results for several collector areas, it can be concluded that $21m^2$ is sufficient to meet the average cooling and heating needs.

Table 4: Collector efficiency in daylight hours

	6-7	7-8	8-9	9-10	10-11	11-12
January	-	0.178	0.474	0.516	0.540	0.550
July	0.428	0.509	0.546	0.565	0.575	0.580

An innovative work for this home is choosing set of collectors to verify the achieved results for useful gain in Tehran. From the achieved collector efficiencies that summarized in Table 2 we find out that due to critical conditions at heating seasons, flat-plate collectors cannot be a logical choice because of the remarkable drop in efficiency in these seasons (blue curve at the right side of the diagram in Fig. 6). So in this case we increase efficiency in winters by making use of some evacuated collectors –the red curve- with the expense of a drop in cooling seasons. So the light green curve is the result and the final calculations are based on the light green curve discretized to two constant values for warm and cold seasons.

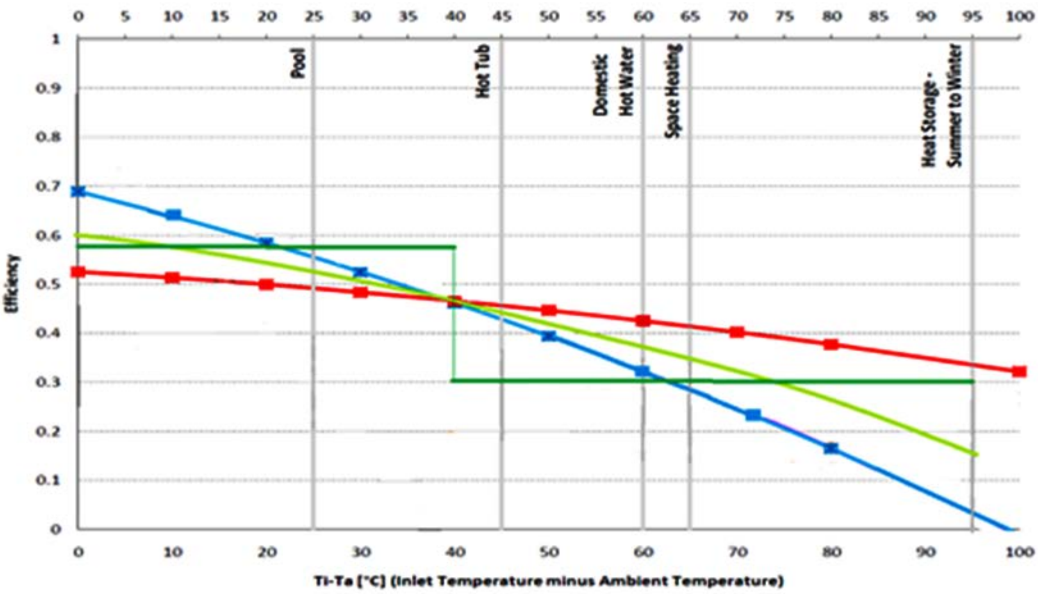

Fig.6. Operating curve of collectors

In conclusion, three evacuated collectors with each area of $3m^2$ has been utilized along with four flat-plate collectors with $4m^2$ surface area to supply the space heating and cooling and DHW needs simultaneously.

5.4. Auxiliary system

The existence of an auxiliary system is essential in the days in which the amount of sunlight is not sufficient or the duration is so short that the storage tank is not able to supply the whole day’s need. Consequently, there should be another system which is run with electricity power. Fig. 7 shows the difference between gain and demand. In the hours in which this amount is negative, auxiliary system has to be used along with storage to meet the demand.

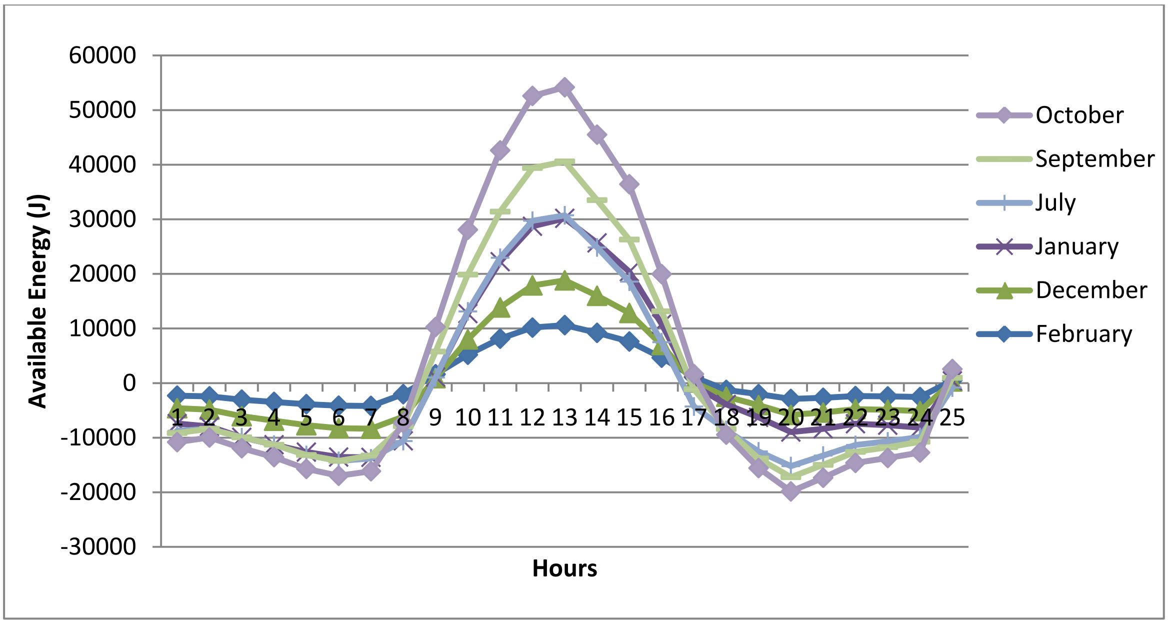

Fig.7. Difference of useful energy and demands in some months

Among various types of auxiliary systems shown in Fig. 8, type B is chosen to provide the house with its needs due to its prior functions. Auxiliary energy is supplied to the water leaving the tank and is controlled to maintain the outlet temperature from the auxiliary heater at a desired level. This method has the advantage of using the maximum possible solar energy from the tank without driving up the collector temperature, but additional heat loss will occur from the auxiliary heater if it has storage capacity.

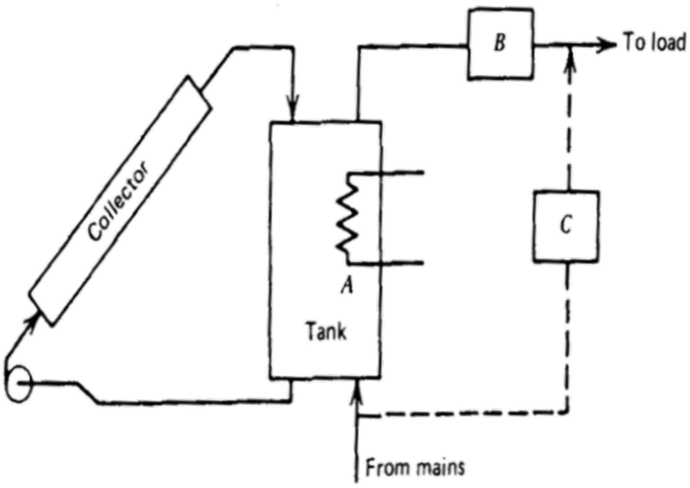

Fig.8. Different types of auxiliary system

6. Lighting

Lighting system is designed to decrease destructive environmental effects and minimize the energy consumption. For this case study, lighting system uses fiber optics and LEDs instead of other common lighting tools. Not containing any toxic materials, fiber optics are suitable to be used at homes especially ZEBs. Also fiber optics can transmit daylight to different zones of home and use an illuminator to deliver light at night without any dazing. “DIALux” 4.1 is utilized for modeling this lighting system. The lighting model for the master bedroom obtained by “DIALux” software is shown in Fig.9 and the wattage and lighting tools used in different zones are summarized in Table 5.

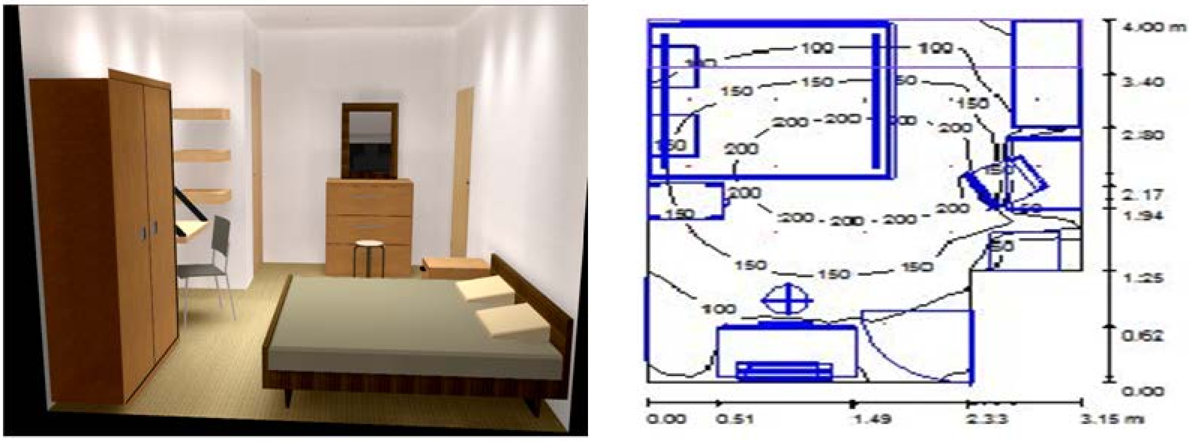

Fig.9. Master bedroom lighting model (left), light distribution in big bedroom (right)

Table 5: Wattage and lighting tools in different zones

Zone	Lighting Tool	Wattage (W)
Living room and kitchen	LED	112
Master bedroom	Fiber optic	17
Small bedroom	Fiber optic	12
Restroom and bathroom	Fiber optic	8
Vestibule	Fiber optic	10
Total	---	163

7. Electricity storage

Systems designed to supply a renewable source of electricity devices are indispensable in the delivery of zero energy building designs. It is comprised of photovoltaic panels, batteries, an inverter-charger unit and electricity loads. Annual electric demand for electrical appliances, lighting, controllers and HVAC auxiliary systems are shown in Table 6.

Table 6: Annual electrical power usage

Annual electricity	kWh
Lighting	310.23
Appliances	2079.72
Controller	240.00
HVAC	2043.59
Total	**4673.54**

The designed PV array is composed of 32 modules to provide electrical demand of the house. The array slope has been set to 30°. The PV parameters are listed in Table 7.

Table 7: PV parameters in the electricity system

Parameters	
Rated power	220W
Open circuit voltage	52.3V
Short circuit current	5.65A
Cell efficiency	19.8%
Module efficiency	17.4%
Area	$1.26m^2$
Cell number	72 cells
Ambient temperature	-20℃ to +46℃

Table 8 is an estimate on how much power the PVs could produce each month through the year in Tehran. Also Fig.10 shows the PV monthly output power.

Table 8: Monthly PV power output

Month	Power (kWh)
January	734.86
February	897.26
March	1004.56
April	1099.68
May	1200.02
June	1352.56
July	1322.4
August	1249.32

September	1210.46
October	973.24
November	834.04
December	716.3
Total	**12594.7**

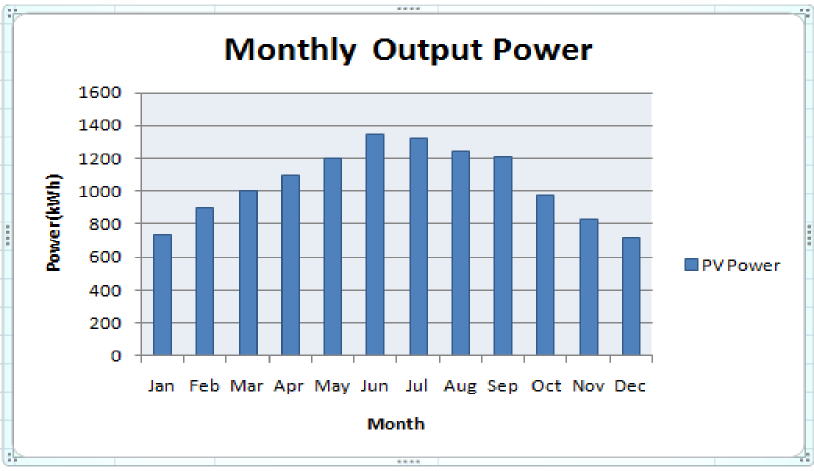

Fig.10. Monthly PV power output

By obtaining these results, we are able to compare the total output power with the total electric loads to come to a conclusion on whether we have a net zero system or not. Fig.11 compares the total output power with the total house loads.

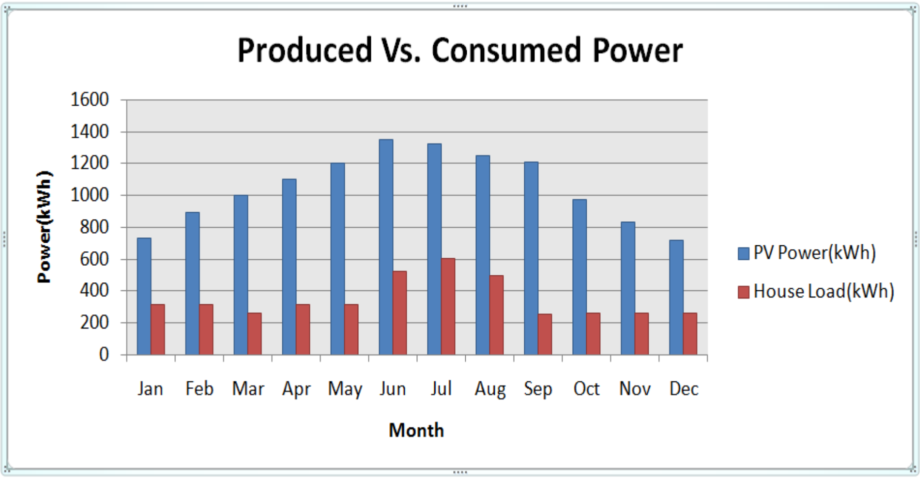

Fig.11. Monthly PV power output vs. house load

Fig.12 helps us to choose the battery size required to provide the need for specific days in which there is no sun. These determined days refer to the climate of Tehran through the year. Relief factor for energy consumption in months is assumed.

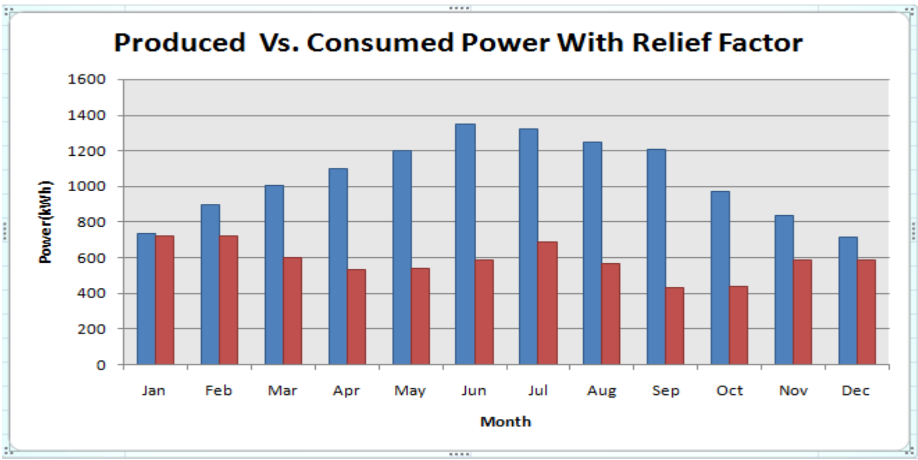

Fig.12. Monthly PV power output vs. house load with relief factor

Considering the results, we used 4 batteries to store produced energy and provide electrical load, and a charger is needed to control charge current and voltage. The battery parameters are shown in Table 9.

Table 9: Battery parameters in the electricity system

Parameters	
Nominal voltage	24VDC
Capacity	400Ah
Battery number	4
Total capacity	1600Ah
Maximum rated energy per month	1152kWh

System designed uses an inverter to convert the direct current (DC) electricity emanates from battery into current electricity (AC) typically required for light and appliance loads with the efficiency of 0.95.In the study, annual house load with relief factor is 7009.97 kWh (Fig. 12) and annual output power from the inverter is 11919.94 kWh.

Monitoring batteries status is an important issue. The monitoring system used in this home is able to calculate consumed electricity in ampere-hours and the state of charge (SoC) of batteries; consequently, we can keep batteries away from over discharging, overcharging and so forth. If the SoC of batteries become less than 30 percent, the control system alarms to decrease energy consumption, and if the SoC becomes less than 10 percent, the control system turns off nonessential appliances and lighting with precedence.

8. Feasibility Study

In each engineering design, the economic study is indispensable. For this typical home, the rate of return is calculated based on two approaches, the present cost of energy and the actual cost with no subsidies from the government. The vast capital and zero running cost for this typical home is treated as though it was interested during the time. Fig. 13 shows the cash flow diagram with the present value of energy in Iran. As it was predictable, it is not economically justified for a private entrepreneur to invest in such a project unless the investment is supported with the government.

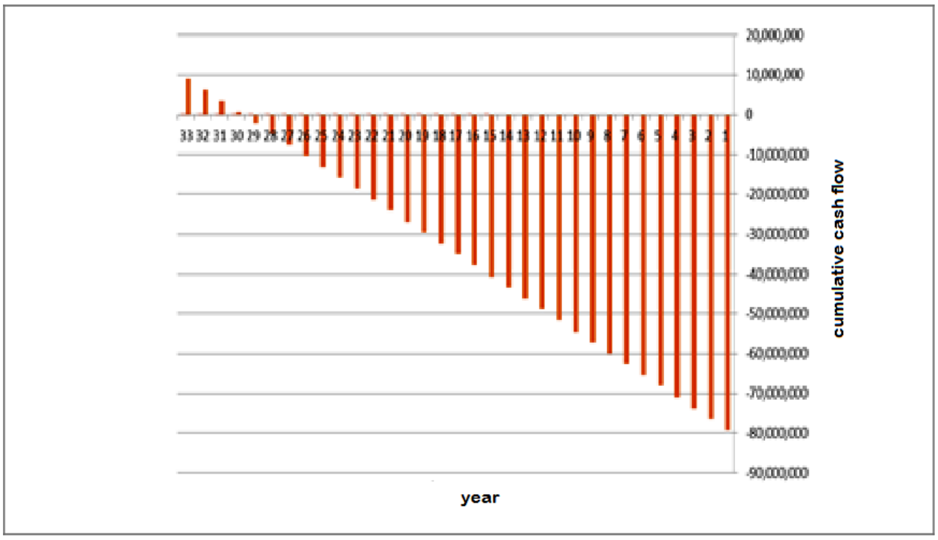

Fig.13. Cash flow diagram with respect to energy subsidies

On the other hand, Fig. 14 indicates that considering the actual costs of energies would result in tangibly less return span and after less than 9 years these homes make profit comparing with conventional ones.

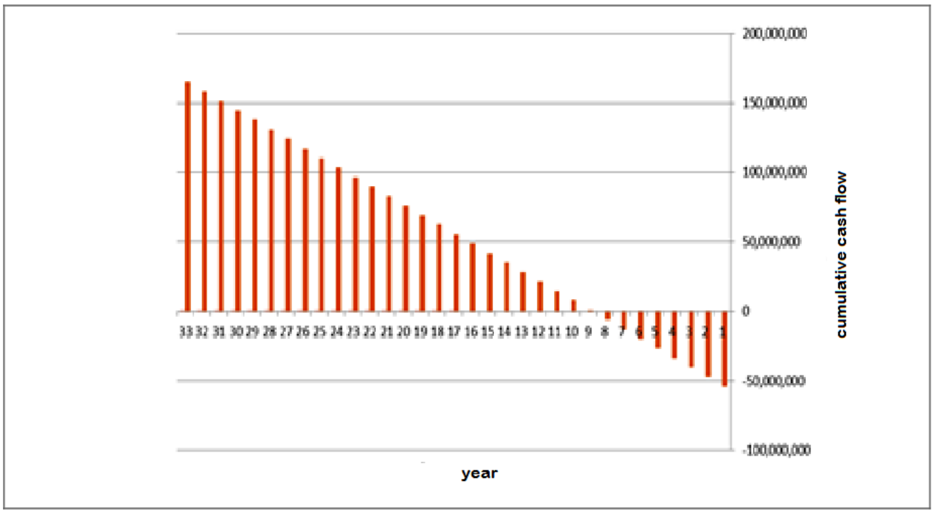

Fig.14. Cash flow diagram with actual costs

Finally it is worth noting that in this calculation the environmental costs and subsequent social costs is ignored and they can solely justify the construction of zero energy buildings regardless of savings in energy. Thus, for a comprehensive study these parameters should be taken into account.

9. Conclusion

In this study the feasibility of solar net zero energy building (ZEB) systems for a typical family of four members in Tehran is investigated. In the first place, solar radiation data and house load are calculated through the designed software and accurate data from local meteorological organization. Applying trombe-wall as a passive strategies results in 40 percents reduction in the house load of master bedroom. A combination of collectors and photovoltaic panels is chosen to supply thermal comfort, hot water and electricity needs. HVAC requirement is met by both passive and active approaches. A solar absorption chiller is utilized to support both heating and cooling need. This system absorbs solar energy through combination of $12m^2$ flat-plate and $9m^2$ evacuated collectors. Furthermore, domestic hot water demand (DHW) is also supplied in part of the designed absorption cycle in order to reduce the size of the equipment and consequently decreases the costs. Results indicate that July is the most critical month which assigns the amount of needed auxiliary energy. Several batteries are used to save extra energy from PV cells during the day for critical conditions such as night-time or cloudy days in which sunlight is not available. To decrease energy consumption and entry of toxic materials to the environment, LEDs and fiber optics are used in lighting system. Fiber optics can transmit natural sunlight to the inner spaces of the house. Off-grid solar photovoltaic system has been chosen for energy storage. It was concluded that it is theoretically possible to achieve the zero energy homes in Tehran. The annual electricity generation is almost 12594.7 kWh while the annual electricity consumption from lighting, appliances, controllers and HVAC is 4673.54 kWh. The remaining electricity can be used to gain financial profit by selling back to the grid.

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Implementation of Simple Measures for Savings Water and Energy Consumption in Kuwait Government Buildings

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Abstract:

This paper gives in details the efforts made by the Public Services Department (PSD) to reduce water and energy consumptions in the Ministry of Social Affairs and Labour's (MOSAL) buildings in Kuwait. PSD manages around 125 buildings distributed over 6 governorates. PSD's efforts included the installation of programmable thermostats for A/C units, urging MOSAL's staff to switch off lighting after working hours, replacement of old A/C and lighting systems by newer systems and installation of shutters and solar films for windows, insulation materials for walls and roofs and low-flow water tools for faucets. These efforts reduced the overall water and energy consumptions by 15 and 25%, respectively, in all MOSAL's buildings. Additionally, MOSAL is planning to collaborate with Kuwait Institute for Scientific Research (KISR) to further reduce water and energy consumptions in MOSAL's buildings by optimizing operation strategies and utilizing new water and energy technologies.

Keywords:
Air-conditioning, lighting system, low-flow water tool, programmable thermostats, solar films.

1. INTRODUCTION

The electrical peak demand and energy consumption are increasing rapidly in the State of Kuwait due to population growth and urban development. The peak electrical demand increased from 6,750 MW in 2011 to approximately 11,850 MW in 2012 (MEW, 2012). The electrical peak demand is expected to reach 28,000 MW in 2025 (AlSayegh et al., 2005). The Ministry of Electricity & Water (MEW) in Kuwait has done a number of measures to reduce the huge annual increase in both peak electrical demand and annual energy consumption. MEW assigned the Kuwait Institute for Scientific Research (KISR) to develop the 1983 Energy Code of Practice, which saved the state more than $15 billion (Meerza and Maheshwari, 2002). Additionally, MEW funded a number of important research activities for KISR to reduce peak electrical demand and annual energy consumption such as energy auditing and peak power reduction strategies in air-conditioning (A/C) buildings, which saved additional peak electrical demand and annual energy consumption. MEW made an important step in 2007 by establishing an executive committee for savings electricity and water in Government Buildings and this committee still exists and conducts periodic meetings. The Ministry of Social Affairs and Labor (MOSAL) is a member in this executive committee. This committee has helped the government agencies to implement number of measures to save water and energy in their buildings.

Most of social affairs activities are executed by MOSAL. The main objective of the government is to distribute social welfares for its Citizens. This can be done through establishing social units to help families socially and financially, nursing homes for youths, supervision of sport clubs and civil organizations. Additionally, MOSAL is responsible to organize and regulate the employments of forging labors at the private sector. Public Services Department (PSD) at MOSAL is responsible to maintain and sustain electrical, mechanical, A/C, pluming and firefighting systems for all MOSAL's buildings. MOSAL manages around 125 buildings in six Kuwaiti governorates. Additionally, water and energy conservation efforts have been given to PSD since 2007.

This paper describes the efforts done by the PSD to reduce water and energy consumption in MOSAL buildings for the past 5 years. Additionally, the paper will give MOSAL's vision for the next 5 years for further reducing water and energy consumption in their buildings.

2. METHODOLOGY

PSD has taken a number of measures to reduce the electrical consumption in about 125 buildings. These measures can be summarized as follows:

1. Installation of programmable thermostats for A/C units and implementing new lighting schedules.

2. Replacement of old A/C units and lighting systems with more energy-efficient systems.

3. Putting in shutters and solar films for windows.

4. Setting up insulation materials for roofs and walls and low-flow water tools.

3. RESULTS AND DISCUSSIONS

PSD implemented a number of measures to reduce water and energy consumption in 125 buildings distributed over 6 governorates. The following sections describe in details these measures:

3.1. Programmable Thermostats and Implementing New Lighting Schedules

PSD installed programmable thermostats for most of A/C units in MOSAL's buildings. Table 1 shows the temperature set point ranges during occupancy and non-occupancy periods. The temperature set points remain the same in the weekends for non-occupancy periods. However, the pre-cooling periods start at midnight for the start of the week to overcome the heat buildup during the weekends and to ensure comfort conditions for the occupancies. Figure 1 illustrates one of the programmable thermostats utilized for the A/C units, which is securely fitted in a metal box to eliminate any changes in temperature settings by MOSAL's staff. This measure has been in action since 2008, received a lot of complains from MOSAL's staff in the beginning and the measure was about to be suspended from MOSAL's upper management. However, PSD staff made a number of experiments with temperature settings to achieve the optimum set point temperatures during occupancy and non-occupancy periods. The ranges of temperature set points, which is shown in Table 1, were acceptable in all MOSAL's buildings. PSD were able to reduce the energy consumption by 20% by installing these programmable thermostats. For the lighting systems, PSD urged MOSAL's staff to switch off the lighting systems after working hours and in non-occupied offices, which started back in 2008. The degree of compliance was about 25-30% in 2008 and increased to more than 60% in 2012 due to increased awareness toward saving energy within MOSAL's staff. This action has reduced good amount of energy consumption for the lighting systems.

Table 1. Temperature Ranges during Occupancy and Non-Occupancy Periods.

Periods	**Temperature Range (^{o}F)**	**Time Range (h)**
Occupancy	70 -72	05:00 – 14:30
Non-occupancy	78 - 80	14:30 – 05:00

(a) (b)

Fig. 1. (a) Model of Programmable Thermostat, and (b) Locked Metal Box for Thermostats.

3.2. Replacement of Air-conditioning and Lighting Systems

PAC and mini-split unites were replaced with newer more energy-efficient units as seen in Fig. 2(a). The savings in energy consumption were ranged between 15 and 20% for these A/C units. Additionally, incandescent lambs with 100 W each and low-efficient fluorescent lambs with old T12 tubes of 20 W and 65 W were utilizes in most of the offices and halls in MOSAL's buildings. A new measure was taken to replace most of these lambs by newer more energy efficient lighting such as compact fluorescent lambs with power range 13 W to 27 W each, as illustrated in Fig. 2(b). The savings in lighting systems reached up to 73%.

(a)

(b)

Fig. 2. (a) Model of new mini-split unit and (b) New type of more energy lighting system

3.3. Shutters and Solar Films for Windows

Windows play significant role in heat gain and air infiltration inside MOSAL's buildings. To reduce these adverse parameters, PSD installed shutters and solar films for most of the windows, as illustrated in Fig. 3, where single and double-glazed windows were used in old and new constructed buildings, respectively. These measures have helped to reduce the heat buildup inside the MOSAL's buildings, which in turn reduce the cooling loads and energy consumption.

(a)

(b)

Fig. 3. (a) Shutters and (b) solar films for windows in MOSAL's Buildings.

3.4. Additional Measures

Additional measures were also taken by PSD to reduce water and energy consumption in new and existing buildings. These additional measures can be summarized as follows:

1. Installation of insulation materials such as extruded polystyrene for roofs and walls in new and existing buildings as per Kuwait Energy Code of Practice [MEW, 2010], as seen in Fig. 4.

2. Putting in low-flow water tools for faucets as shown in Fig. 5.

Fig. 4. Type of insulation materials used for walls and roofs.

Fig. 5. Type of low-flow water tool to reduce water consumption in faucets.

4. FUTURE PLAN

MOSAL is planning to collaborate with Kuwait Institute for Scientific Research (KISR) to develop strategic energy and water conservation plan for the next 5 years. KISR has huge experiences in reducing water and energy consumption in new and existing buildings for the past 5 decades. Therefore, the main objectives of this plan will be as follows:

1. To further reduce water and energy consumption in all MOSAL's buildings.

2. To train PSD's staff to carry out water and energy conservation measures individually in the future.

The plan will consist of a number of important steps to ensure successful execution. These steps can be summarized as follows:

1. Online monitoring of water and energy to establish base case water and energy consumption in all MOSAL's buildings.

2. Conduct in-depth energy audits for all MOSAL's buildings.

3. Establish new operation strategies based on feedback from online monitoring and energy audits.

4. Implement new technologies to further reduce water and energy consumption in MOSAL's buildings.

5. Establish water and energy savings after implementing new operation strategies and technologies compared against base case scenarios.

6. Develop training program based on the outcomes of this plan for engineers and technicians in other government and institutional agencies in Kuwait.

5. CONCLUSIONS AND RECOMMENDATIONS

PDS has implemented a number of measures to reduce water and energy consumptions after the establishing of Executive Committee to save water and energy in government buildings by MEW in Kuwait back in 2007. These measures included the installation of programmable thermostats for A/C units, urging MOSAL's staff to switch off lighting after working hours, replacement of old A/C and lighting systems by newer systems, installation of shutters and solar films for windows and insulation materials for walls and roofs and low-flow water tools for faucets. These measures reduced the overall water and energy consumptions by 15 and 25%, respectively. Additionally, MOSAL is planning to collaborate with KISR to further reduce water and energy consumptions in MOSAL's buildings by optimizing operation strategies and utilizing new water and energy technologies.

6. ACKNOWLEDGMENTS

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Investigation of a Novel Solar Assisted Water Heating System with Enhanced Energy Yield for Buildings

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Abstract:
This paper presented the concept, prototype application, operational performance and benefits relating to a novel solar assisted water heating system for building services. It was undertaken through dedicated theoretical analysis, computer simulation and experimental verification. The unique characteristic of such system consists in the integrated loop heat pipe and heat pump unit (LHP-HP), which was proposed to improve solar photovoltaic (PV) generation, capture additional solar heat, and therefore enhance overall solar energy yield. The evaluation approaches derived from the first-law thermodynamics and the standard/hybrid system performance coefficients (COP/$COP_{PV/T}$) were developed for the comprehensive assessments. Under the featured weather conditions, the mean electrical, thermal and overall energetic efficiencies of the module were tested around 9.12%, 38.13% and 47.25% respectively. Whilst the COP and $COP_{PV/T}$ values of entire system were measured at about 5.51 and 8.81 averagely. Moreover, a general comparison of this prototype system against the conventional solar/air energy systems was simply discussed.

Keywords:
Efficiency; *COP*; Heat pump; Loop heat pipe; PV;

1. Introduction

In EU, building sectors account for approximately 40% of the primary energy consumption and 36% of total carbon emission [EU statistical pocket book 2007/2008]. Improving the building energy efficiency shall provide a substantial contribution towards attaining the EU's energy 'decarburization' targets. To achieve this goal, the high fraction of locally available renewable energy sources in energy mix will become necessary to achieve a significantly reduced energy dependence of buildings. Solar energy is normally regarded as the most important renewable energy source for local heat/cold or power production. The solar assisted building services engineering could be potential solutions for both enhanced energy performance and reduced operating cost in contemporary built environment. To accelerate the process, improving the overall solar conversion efficiency is regarded as the top priority in solar technology innovation and building services. It is recognized that the PV's efficiency falls with its cells temperature rise [Zondag et al., 2002]. To control the cell temperature, the measures were applied to remove the accumulated heat from the PV back surface and further to make utilization of the additional heat for servicing buildings. These approaches, known as PV/Thermal (PV/T) technology, have been proven effectively in increasing solar conversion ratio and making economic use of the solar energy in buildings.

In recent years, numerous researchers has made efforts to develop various PV/T technologies including those by air, water, refrigerant and heat pipe [X Zhang et al., 2012], whose research results indicated the excellent effectiveness of the PV/T devices in increasing solar energy yield. However, use of these PV/T devices has also discovered several inherent technical shortfalls, e.g., low thermal capacity of the media, risk of leakage, uneven heat distribution, and hazard of potential freezing. To overcome these, a unique loop heat pipe structure with the top positioned three-ways tube was initiated. This structure, in combination with the PV layer, can form a modular PV/T collector. This loop-heat-pipe based PV/T type may have potential to overcome the difficulties existing in above systems and have the advantages lying in: (1) efficient thermal performance for a distant travel; (2) hermetically sealed vessel without risk of fluid leakage; (3) homogeneous built-in capillary force leading to even heat distribution; (4) availability for use of anti-freezing liquid; (5) top feeding structure to avoid 'dry-out' problem of the upper liquid film in conventional heat pipes [A. Faghri, 1995].When combining the operation of heat pump, it's therefore expect to achieve highly efficient heat and electricity generation using solar energy.

2. System description

The proposed photovoltaic/loop-heat-pipe heat pump (PV/LHP-HP) water heating system is schematically shown in Fig. 1. This system comprises a modular PV/LHP solar collector, an electricity control/storage unit, vapour/liquid transportation lines, a flat-plate heat exchanger acting as the condenser of the heat pipe and the evaporator of heat pump cycle, a hot water tank embedded with a coil-type condenser, a compressor, and an expansion valve.

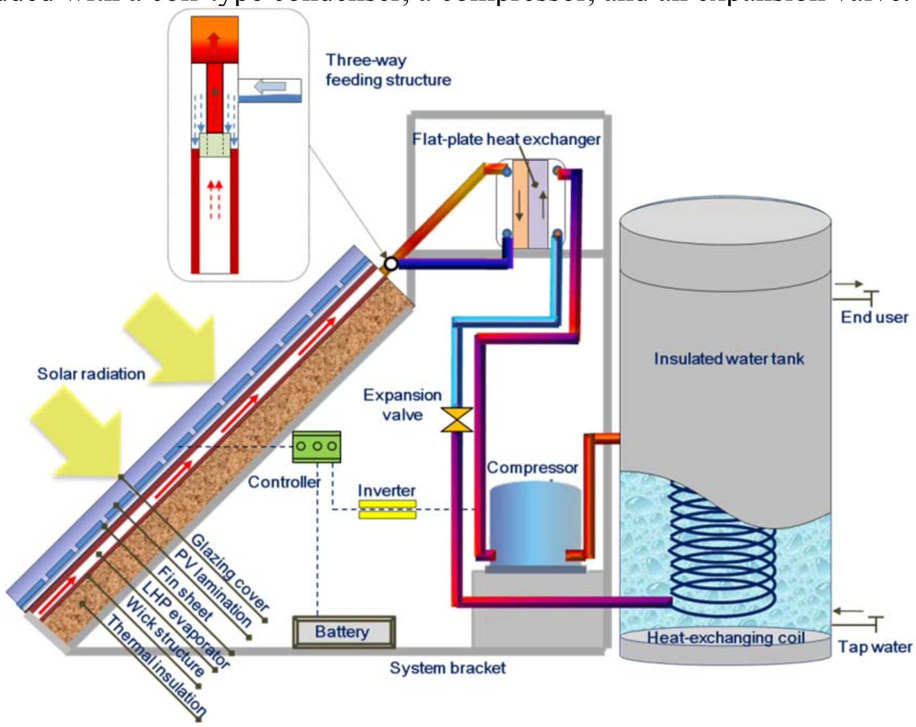


Fig. 1: Schematic of the PV/LHP heat pump system

The LHP evaporator in Fig.1 is an externally finned and internally wicked heat pipe with the three-way tube on the top. This pipe structure could deliver evenly distributed water film across the heat pipe wall from the top, and keep constant saturation of the wall all the way downside, thus preventing the 'dry-out' potential of the water across the wall. The three-way tube, meanwhile, could also deliver the vapour upward to the flat-plate exchanger through the vapour transportation line. This will create a clear separation between the liquid and vapour flows within the heat pipe. In the module, the LHP evaporator is placed underneath the PV layer to extract heat from the PVs. During the operation, this part of heat will be delivered to the heat exchanger through vapour transportation line, within which heat transfer between the heat pump refrigerant and heat pipe working fluid will occur. This interaction will lead to condensation of the heat pipe working fluid and subsequently the condensed liquid will return to the LHP evaporator via the liquid transportation line, thus completing the heat pipe fluid circulation. Meanwhile in the heat pump cycle, the liquid refrigerant will be vaporized in the heat exchanger, which, driven by the compressor, will be then upgraded into higher pressured, supersaturated vapour, and further release heat into the tank water via the coil exchanger, leading to temperature rise of the tank water. Also, the heat transfer within the coil exchanger will lead to condensation of the high pressured vapour, which, passing via the expansion valve, will be downgraded to the low pressure liquid refrigerant. This refrigerant will undergo the evaporation process within the heat exchanger, thus completing the entire process of heat pump cycle. The ideal thermodynamic process of the refrigerant is shown in Fig. 2.

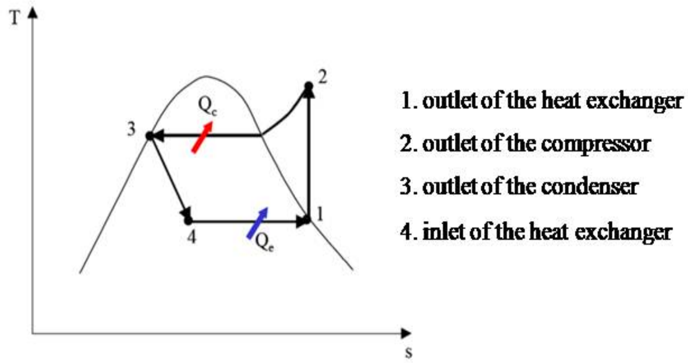


Fig. 2: Indication of the ideal heat pump thermodynamic cycle

The distinct features of the PV/LHP-HP system lie in (1) temperature of the LHP working fluid could be controlled to a lower level through adjustment of the refrigerant evaporation pressure in the heat pump; this will lead to the reduced PV cells temperature, improved module electrical and thermal efficiencies, and increased solar output per unit of absorbing surface; (2) refrigerant temperature/pressure can be raised up to a given level, enabling heat to be transferred from the refrigerant to the tank water; (3) electricity required for driving the compressor can be further delivered from the PV power when designing appropriately, thus creating a near-to-zero-carbon water heating operation. It can be predicted that more or less electricity surplus or deficiency may occur, which can be balanced through the battery storage or connection to the national grid. This system may be installed on a building where the PV/LHP modules could be attached to its façade or roof. For this application, the heat exchanger could be positioned at the upper side of the modules, while the heat pump cycle installed inside of the building. Alternatively, this system can also be separately installed as an independent heat and power generation unit when necessary.

3. Mathematical analysis

For this system, the transient mathematical model involves six energy balance equations (Fig. 3): (i) heat balance equation of the glazing cover; (ii) heat balance equation of the PV lamination; (iii) one-dimensional unsteady-sate heat conductance of the fin sheet; (iv) heat balance equation of the loop heat pipe operation; (v) heat balance equations of the heat pump cycle and (vi) water tank.

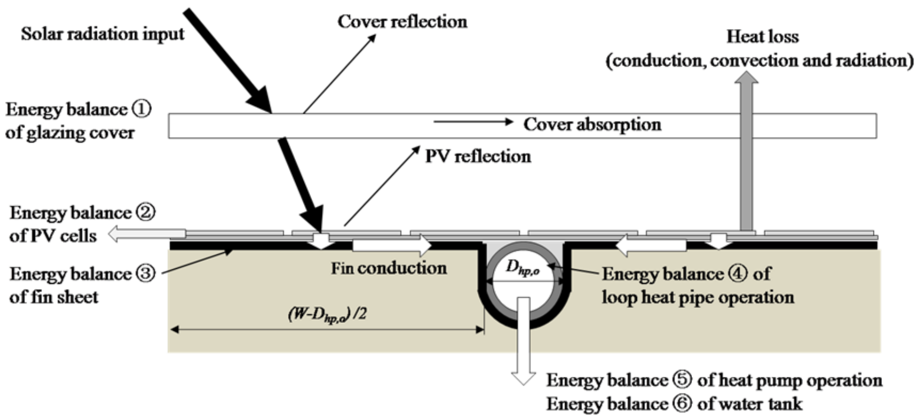


Fig. 3: Schematic of the energy balances involving in the system

3.1. Heat balance equation of the glazing cover

To describe the time dependency of heat flows on a single glazing cover, the corresponding energy balance equation is given by

$$\rho_c c_c \delta_c \frac{\partial T_c}{\partial \tau} = I\alpha_c + \left(h_{c,p-c} + h_{R,p-c}\right)\left(T_p - T_c\right) - \left(h_{c,c-a} + h_{R,c-a}\right)\left(T_c - T_a\right) \tag{1}$$

$$h_{c,p-c} = \frac{k_a}{\delta_a}\left\{1 + 1.446\left(1 - \frac{1708}{Ra_a \cos\theta}\right)^{+}\left[1 - \frac{1708\sin(1.8\theta)^{1.6}}{Ra_a \cos\theta}\right] + \left[\left(\frac{Ra_a \cos\theta}{5830}\right)^{0.333} - 1\right]^{+}\right\} \tag{2}$$

$$Ra_a = \frac{g\left(T_p - T_c\right)\delta_a^{\,3}}{\nu_a^{\,2} T_{a,m}} \mathrm{Pr}_a \tag{3}$$

$$T_{a,m} = \left(T_p + T_c\right)/2 \tag{4}$$

$$h_{R,p-c} = \frac{\sigma\left(T_p + T_c\right)\left(T_p^2 + T_c^2\right)}{\left(1/\varepsilon_p\right) + \left(1/\varepsilon_c\right) - 1} \tag{5}$$

$$h_a = h_{c,c-a} = \frac{8.6V^{0.6}}{L^{0.4}} \tag{6}$$

$$h_{R,c-a} = \varepsilon_c \sigma\left(T_c + T_s\right)\left(T_c^2 + T_s^2\right) \tag{7}$$

$$T_s = 0.0552 T_a^{1.5} \tag{8}$$

3.2. Heat balance equation of the PV lamination

The energy balance equation on the combined PV lamination can be written as

$$\rho_p c_p \delta_p \frac{\partial T_p}{\partial \tau} = \left[I(\tau_c \alpha)_b (1-\beta_p) + I(\tau_c \alpha)_p \beta_p - Q_e \right] - (T_p - T_f)/R_{p-f} A_p - (h_{c,p-c} + h_{R,p-c})(T_p - T_c) \tag{9}$$

The overall transient solar transmittance for a single cover becomes

$$\tau_c = \frac{\tau_{c,\alpha}}{2} \left\{ \frac{1-r_{\parallel}}{1+r_{\parallel}} \left[\frac{1-r_{\parallel}}{1-(r_{\parallel}\tau_{c,\alpha})^2} \right] + \frac{1-r_{\perp}}{1+r_{\perp}} \left[\frac{1-r_{\perp}}{1-(r_{\perp}\tau_{c,\alpha})^2} \right] \right\} \tag{10}$$

$$\tau_{c,\alpha} = e^{\left(-\frac{K\delta_c}{\cos(\theta_2)}\right)} \tag{11}$$

$$\theta_2 = \sin^{-1}\left(\frac{\sin\theta_1}{n_g}\right) \tag{12}$$

$$\cos(\theta_1) = \sin(L_m - \theta)\sin(\delta_m) + \cos(L_m - \theta)\cos(\delta_m)\cos(h_m) \tag{13}$$

The thermal resistance from PV cells to the fin sheet is calculated

$$R_{p-f} = R_p + R_{EVA} + R_{ei} = \frac{\delta_p}{k_p A_p} + \frac{\delta_{EVA}}{k_{EVA} A_p} + \frac{\delta_{ei}}{k_{ei} A_p} \tag{14}$$

The corresponding electricity output per unit area is defined

$$q_e = I(\tau_c \alpha)_p \beta_p \eta_{rc} \left[1 - \beta_{PV} (T_p - T_{rc}) \right] \tag{15}$$

3.3. One-dimensional unsteady-sate heat conductance of the fin sheet

The time-dependent heat conductance on the PV-based fin sheet can be tackled as a typical one-dimensional unsteady-state heat transfer on an infinite flat-plate and its heat balance equations are expressed as

$$\begin{cases} \rho_f c_f \delta_f \dfrac{\partial T_f}{\partial \tau} = k_f \delta_f \dfrac{\partial^2 T_f}{\partial x^2} + \left(T_p - T_f\right) / R_{p-f} A_p - \left(T_f - T_a\right) / \left(R_{f-a} A_{fs} + 1 / h_a A_{fe}\right) & (16) \\ \rho_f c_f \delta_f \dfrac{\partial T_{f,11}}{\partial \tau} = \left(T_{p,11} - T_{f,11}\right) / R_{p-f} A_p - \left(T_{f,11} - T_{hp,w}\right) / R_{f-hp} A_{fc} - \left(T_{f,11} - T_a\right) / R_{f-a} A_{fs} & (17) \end{cases}$$

The initial temperature and boundary conditions are described

$$\begin{cases} T\left(x,0\right) = T_{f,i}{}^{0}, \tau = 0 \\ -k_f \dfrac{\partial T}{\partial x}\Big|_{x=0} = h_a \left(T_{f,0} - T_a\right), \tau > 0 \\ T\left(\dfrac{W}{2}, \tau\right) = T_{f,11}, \tau > 0 \end{cases} \quad (18)$$

The thermal resistances of fin sheet insulation to air, and fin sheet to heat pipe external wall are respectively written by

$$R_{f-a} = \frac{\delta_{fs}}{k_{fs} A_{fs}} \quad (19)$$

$$R_{f-hp} = \frac{\delta_f}{k_f A_{fc}} \quad (20)$$

3.4. Heat balance equation of the loop heat pipe

The heat balance equation for the loop heat pipe can be described as

$$\frac{1}{4}\pi\left(D_{hp,o}{}^2 - D_{hp,in}{}^2\right)\rho_{hp} c_{hp} L_{hp} \frac{\partial T_{hp,w}}{\partial \tau} = \left(T_{f,11} - T_{hp,w}\right) / R_{f-hp} A_{fc} - \left(T_{hp,w} - T_{r,m}\right) / R_{hp-r} - \left(T_{hp,w} - T_a\right) / R_{hp-a} \quad (21)$$

$$R_{hp-a} = \frac{\ln\left(D_{hp,o} / D_{hp,in}\right)}{2\pi L_{hp} k_{hp}} + \frac{1}{h_a A_{hp}} \quad (22)$$

$$R_{hp-r} = R_{hp,w} + R_{wi} + R_{lf} + R_{hx} + R_r \quad (23)$$

$$R_{hp,w} = \frac{\ln\left(D_{hp,o} / D_{hp,in}\right)}{2\pi L_{hp} k_{hp}} \tag{24}$$

$$R_{wi} = \frac{\ln\left(D_{hp,in} / D_{v,e}\right)}{2\pi L_{wi} k_{wi}} \tag{25}$$

$$k_{wi} = \frac{k_l \left[\left(k_l + k_s\right) - \left(1 - \varepsilon_{wi}\right)\left(k_l - k_s\right)\right]}{\left[\left(k_l + k_s\right) + \left(1 - \varepsilon_{wi}\right)\left(k_l - k_s\right)\right]} \tag{26}$$

$$\varepsilon_{wi} = 1 - \frac{1.05\pi n_{wi} D_{wi}}{4} \tag{27}$$

$$R_{lf} = \frac{\ln\left[D_{hx,in} / \left(D_{hx,in} - 2\delta_{lf}\right)\right]}{2\pi L_{lf} k_{lf} \left(N_{hx} / 2 - 1\right)} \tag{28}$$

$$R_{hx} = \frac{\ln\left(D_{hx,o} / D_{hx,in}\right)}{2\pi\left(H_{hx} / 2\right) k_{hx} \left(n_{hx} / 2 - 1\right)} \tag{29}$$

$$R_r = \frac{1}{h_r A_{hx,r} \left(N_{hx} / 2\right)} \tag{30}$$

$$h_r = h_{r,l} \left[\left(1 - x_r\right)^{0.8} + \frac{3.8 x_r^{0.76} \left(1 - x_r\right)^{0.04}}{\mathrm{Pr}_r^{0.38}}\right] \tag{31}$$

$$h_{r,l} = \frac{Nu_{r,l} k_{r,l}}{D_{hx,in}} \tag{32}$$

$$Nu_{r,l} = 0.023\, \mathrm{Re}_{r,l}^{0.8}\, \mathrm{Pr}_{r,l}^{0.4} \tag{33}$$

$$\mathrm{Re}_{r,l} = \frac{m_r \left(1 - x_r\right) D_{hx,in}}{A_{hx,r} \rho_{r,l} \nu_{r,l} \left(N_{hx} / 2\right)} \tag{34}$$

$$\mathrm{Pr}_{r,l} = \frac{\mu_{r,l} c_{p,lr}}{k_{r,l}} \tag{35}$$

3.5. Heat balance equation of the heat pump cycle and water tank

The solar heat delivered to the heat pump operation is theoretically given by

$$\frac{\partial\left(M_r H_{r,e}\right)}{\partial \tau} = \left(T_{hp,w} - T_{r,m}\right) / R_{hp-r} - \left(T_{hp,w} - T_a\right) / R_{hp-a} \tag{36}$$

The heat pump condenser heat is fully filled into the water, defined as

$$M_w c_w \frac{\partial T_w}{\partial \tau} = \frac{\partial\left(M_r H_{r,c}\right)}{\partial \tau} - \left(T_w - T_a\right) / R_{w-a} \tag{37}$$

$$R_{w-a} = \frac{\ln\left(D_{ws,o} / D_{ws,in}\right)}{2\pi L_{ws} k_{ws}} + \frac{1}{h_a A_w} \tag{38}$$

To numerically solve above equations, the time step, $\Delta\tau$, and space step, Δx, are respectively set at 1min and 22mm, the grouped energy derivation equations can be discretized using the forward and centre finite differential method. An initial temperature distribution (τ=0) from module cover to water in tank will be assumed before starting iteration. The corresponding initial and boundary conditions are obtained from the experimental records.

3.6. Module efficiencies and system performance indicators

The overall energy efficiency is yielded from the first law of thermodynamics and indicates the percentage of the energy converted from the solar radiation, defined as

$$\eta_e = \frac{\int_{\tau_0}^{\tau_{k+1}} Q_e d\tau}{\int_{\tau_0}^{\tau_{k+1}} A_m I d\tau} \tag{39}$$

$$\eta_{th} = \frac{\int_{\tau_0}^{\tau_{k+1}} Q_{th} d\tau}{\int_{\tau_0}^{\tau_{k+1}} A_m I d\tau} \tag{40}$$

$$\eta_o = \eta_e + \eta_{th} \tag{41}$$

The standard system performance coefficient (COP) is evaluated

$$COP = \frac{\int_{\tau_0}^{\tau_{k+1}} Q_w d\tau}{\int_{\tau_0}^{\tau_{k+1}} (Q_w - Q_{th}) d\tau} \quad (42)$$

As such PV/LHP system yields not only heat but also electricity, a comprehensive system coefficient of thermal-and-electrical performance ($COP_{PV/T}$) is defined, where the solar electricity is converted into the equivalent thermal energy through use of average electricity-generation efficiency (commonly 38% [Huang, 2001]) in a coal-fired power plant.

$$COP_{PV/T} = \frac{\int_{\tau_0}^{\tau_{k+1}} (Q_w + Q_e / 0.38) d\tau}{\int_{\tau_0}^{\tau_{k+1}} (Q_w - Q_{th}) d\tau} \quad (43)$$

To find out the discrepancy between the theoretical and experimental results, the root mean square percentage deviation (RE) will be evaluated using the following expression:

$$RE = \sqrt{\frac{\sum [100 \times (X_e - X_s) / X_e]^2}{N}} \quad (44)$$

where, X_e and X_s represents the experimental and simulated values respectively.

4. Results and discussion

To validate the computer simulation, the model was adjusted to the identical set-ups as for the outdoor conditions and system geometry/operational parameters. The discrepant results obtained from the comparison were put into calculation of the model accuracy. Further, dedicated analyses and discussions towards the modelling/testing results were conducted.

4.1. Experimental set up and testing

A prototype of PV/LHP-HP system was constructed in Shanghai, China and run for testing under the practical outdoor conditions. The PV/LHP module, with an effective absorbing area of $0.612m^2$, was fixed to the 30^o tilted frame, and fitted with the single glazing cover on top. The PV cells, consisting of totally 36 (4 × 9 array) pieces each with sizes of 125 × 125 × 0.3 (mm × mm × mm), took up nearly 90% of the absorbing surface. Table 1 presents the values of the characteristic parameters relating to the PV cells under the standard testing conditions. When making up the PV lamination, a black 5052 aluminum alloy sheet, coated with 20μm anodic oxidation film to prevent electrical transmission, was used to replace the conventional TPT (tedlar-Polyester-tedlar) base-board of PV cells. A 5 mm thick aluminum Ω-type fin sheet, embracing a wicked pipe (with 160 x 60 copper meshes), was adhered to the PV base-board using silicon sealants. This pipe, connecting to the liquid and vapour transportation lines and condensing heat exchanger, formed up a loop that was evacuated and then filled with 75ml of water/glycol mixture (95%/5%) as working fluid. Further, the system employed a 1kW-rating compressor with evaporation/condensation temperatures of 10^{o}C/55^{o}C, which was charged with 300g of R134a refrigerant. A 35-liter water tank with built-in cooper heat exchanging coils was also installed and connected to the heat pump. The electrical parts of the system include a 12V (10A) controller, 500W DC/AC inverter, a 100AH (12V) battery, and the connection wires. The insulation materials including the foamy polyurethane for piping and polystyrene board for exchangers were also applied to minimize the heat loss of the system components.

Table1: Characteristics of the PV module under standard testing conditions

At short-circuit current	$I_{SC} = 5.54\ A,\ V_{SC} = 0\ V$
At open-circuit voltage	$I_{OC} = 0\ A,\ V_{OC} = 22.32\ V$
At the maximum power point	$I_{mp} = 4.89\ A,\ V_{mp} = 18.23\ V\ (P_{mp} = 89.1\ W,\ \eta_o = 16.8\%)$

The outdoor experiment was performed on 21st November 2011 in Shanghai, China (31^{o}11'N and 121^{o}29' E). The daily variation of solar radiation and ambient temperature are shown in Fig. 4. The initial water temperature in the tank was measure at around 14.38^{o}C. The testing was operated from 8:40 to 16:20 and while testing, all the sensors/instruments were placed in the positions, and were linked to a DT500 data logger and then to a computer. The testing data were recorded every minute interval.

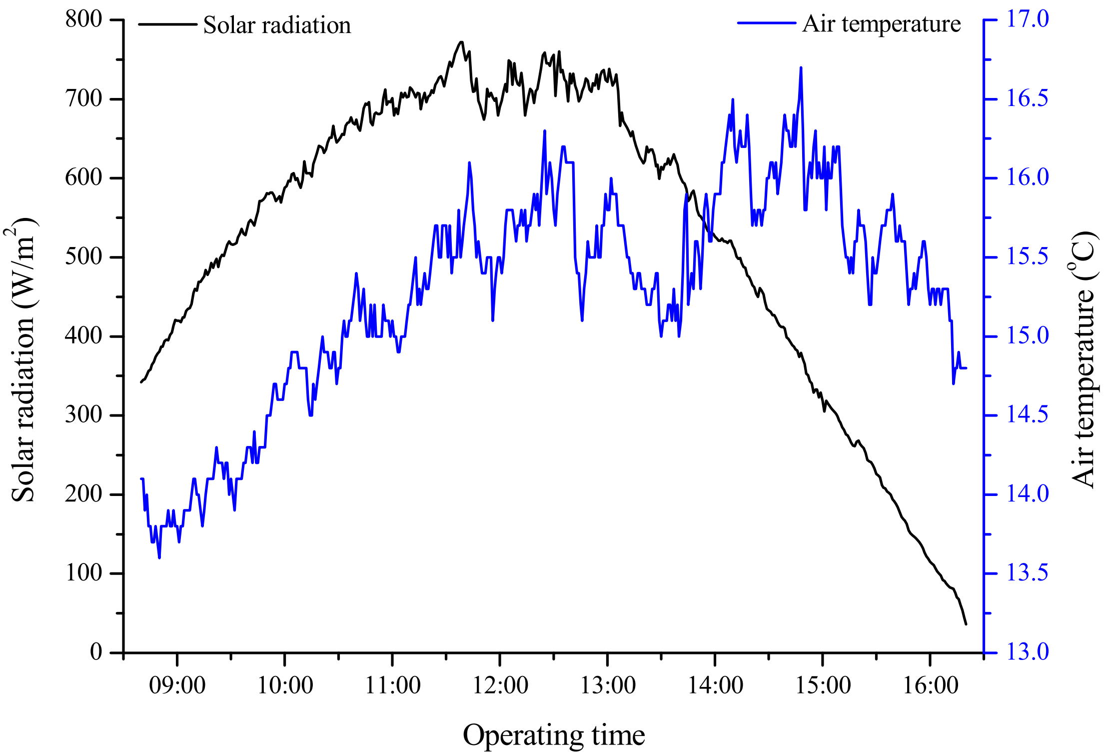


Fig. 4: Daily solar radiation and air temperature

4.2. Photovoltaic power output and module electrical energy efficiency

Fig. 5 provided the comparison between modelling and testing results of the photovoltaic power and module electrical energy efficiency. The average modelling/testing solar electrical gain and the corresponding efficiencies were respectively 29.91W/29.45W and 9.23%/9.12%, giving an excellent mutual agreement with the mean deviation of 1.45%. The daily electrical yield was found quite similarly as the solar radiation to gradually increase in the morning while falling down significantly after it reached the peak value at noontime. The electrical energy efficiency was observed to slightly increase at the start-up stage and largely decreased at the end-up stage, while it remained relatively smooth during most of the testing period. The reason for the parabolic power curve was mainly due to the variation of solar radiation intensity and its incident angle. It is well known that stronger solar radiation and smaller incident angle of the solar beam would result in more absorbed solar energy and therefore higher solar electrical gain, which, during this experiment, ideally appears at the noontime and became less satisfactory in the morning and afternoon. The electrical energy efficiency usually changes oppositely with the solar incident angle and PV cells' temperature, and the ultimate electrical energy efficiency would be determined depending upon whose transient impact is greater. Normally, a lower PV temperature will appear in the early morning or late afternoon while the solar incident angle happens to be in the larger magnitude. For this dedicated testing, it's obvious that the solar incident angle was the primary governing factor in the early morning and later afternoon, resulting in the smaller electrical energy efficiency; while these two parameters became equivalent and cause less fluctuated electrical energy efficiency during rest operating period.

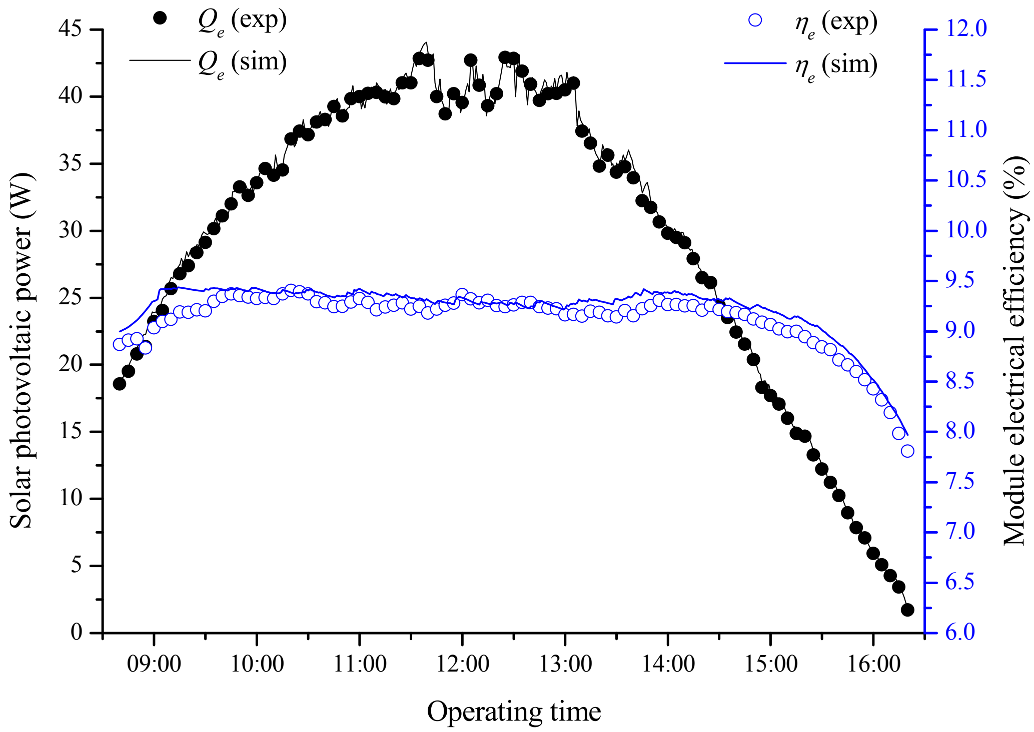


Fig. 5: Daily power output and module electrical energy efficiency versus operating time

4.3. Solar heat gain and module thermal energy efficiency

Variation of both solar heat gain and module thermal energy efficiency versus the operating time was given in Fig. 6. The average modelling/testing solar heat and the corresponding thermal energy efficiencies were respectively about 122.87W/120.08W and 38.76%/38.13%, giving a reasonable mutual agreement with the mean deviation of 5.20%. It is found the daily solar thermal yield also behaved a parabolic curve which sharply grew in the morning and performed a slightly-smooth declination after about 13:00 in the afternoon. The features of transient solar radiation and incident angle primarily affected the energy absorption of the module and also characterized its corresponding daily thermal performance. Meanwhile, as the air temperature nearly kept increasing most of the day, less heat loss will occur in the afternoon, enabling a relatively-smooth decrease of the solar heat gain. The module thermal energy efficiency was observed to sharply increase in both the start-up and end-up stages, and remained relatively steady during rest operating period. As the heat pump was run at a controlled evaporating temperature, this can be explained that when the system started to operate, the module-self warming up and lower surrounding air temperature would negatively reduced the instant evaporating heat gain of refrigerant and thus weakened the thermal energy efficiency; while in the operation end, the delayed warm module temperature and higher surrounding air temperature would positively enlarge the transient evaporating heat gain of refrigerant and therefore strengthened the thermal energy efficiency. During rest operation period, a less-fluctuated thermal efficiency can be obtained by reason of the stable refrigerant evaporating temperature and the equivalent overall functions of both solar incident angle and air temperature.

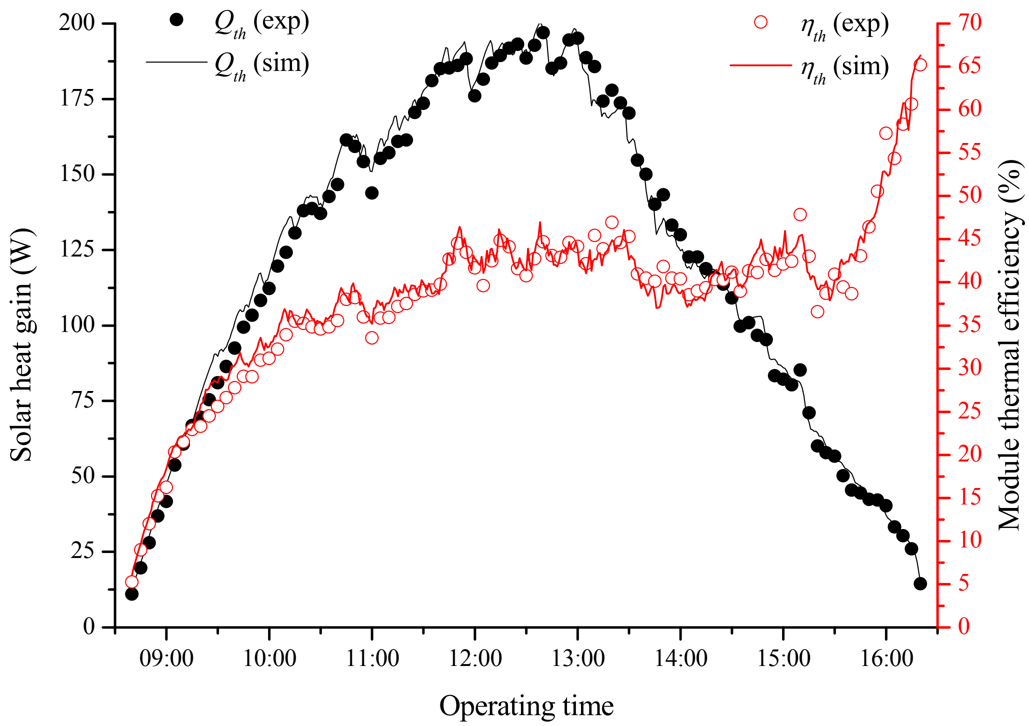


Fig. 6: Daily solar heat gain and module thermal energy efficiency versus operating time

4.4. Heat pump condensing capacity and system performances

Fig. 7 illustrated the variation of daily heat pump condensing capacity, standard system performance coefficient (*COP*) and the overall performance coefficient of this hybrid system ($COP_{PV/T}$). The average modelling/testing results of water heat gain, *COP* and $COP_{PV/T}$ were respectively about 148.11W/146.86W, 5.88/5.51 and 9.28/8.81, giving the mutual agreements with the mean deviations of 4.58%, 8.80% and 9% respectively. The daily varying discipline of the heat pump condensing capacity was found nearly the same as that of the daily absorbed solar heat, as it was only upgraded by inputting the fixed compressor work. The typical *COP* values stayed nearly constant all the day in that the evaporating and condensing temperatures of the heat pump cycle were set fixed. The $COP_{PV/T}$ of this hybrid prototype system was found to significantly decrease during the early half-hour operation, and then remained relatively stable. This is because in the early testing period, the electrical output was the primary impacting factor of $COP_{PV/T}$ at that time being, which was much larger than the system heat gain and resulted in the considerably high $COP_{PV/T}$ values; while with the rapid increase of system heat gain, the thermal yield, based on thermodynamic cycle of the heat pump, became the crucial impacting factor and caused the $COP_{PV/T}$ becoming much smaller and steady as close to the *COP*s. In this case, the electrical output was a positive addition to the system overall performance, and thus made the $COP_{PV/T}$ larger than typical *COP* values.

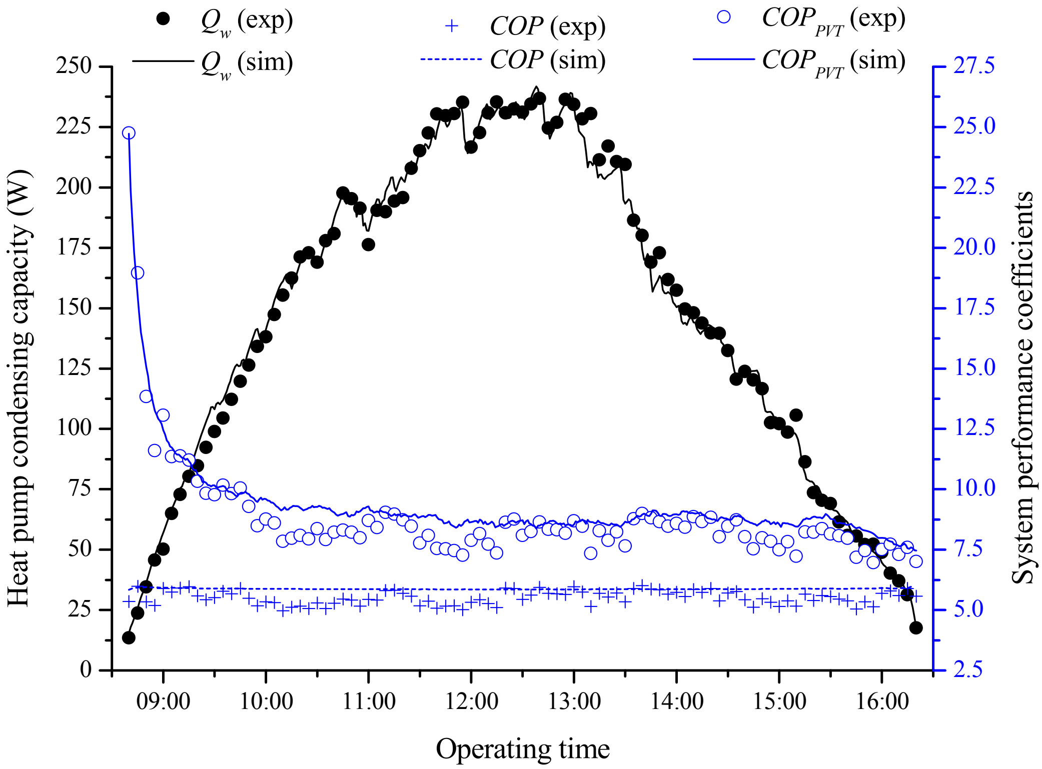


Fig. 7: Daily water heat gain and system performances versus operating time

It should be noted that as the heat pump compressor worked intermittently, the amount of the compressor electrical consumption were recorded every intermittent period and averagely divided by each interim time length. In this circumstance, the measured system *COP* and $COP_{PV/T}$ values appeared to be less accurate than other parameters.

4.5. Error analysis

It has been found that certain differences were in existence between the modelling and testing results of the system's characteristic parameters, as indicating in Table 2. For all sets of comparison, the mean deviations were no larger than 9%, which were acceptable in terms of general engineering applications, and indicated that the established model can predict the system performance at a reasonable accuracy.

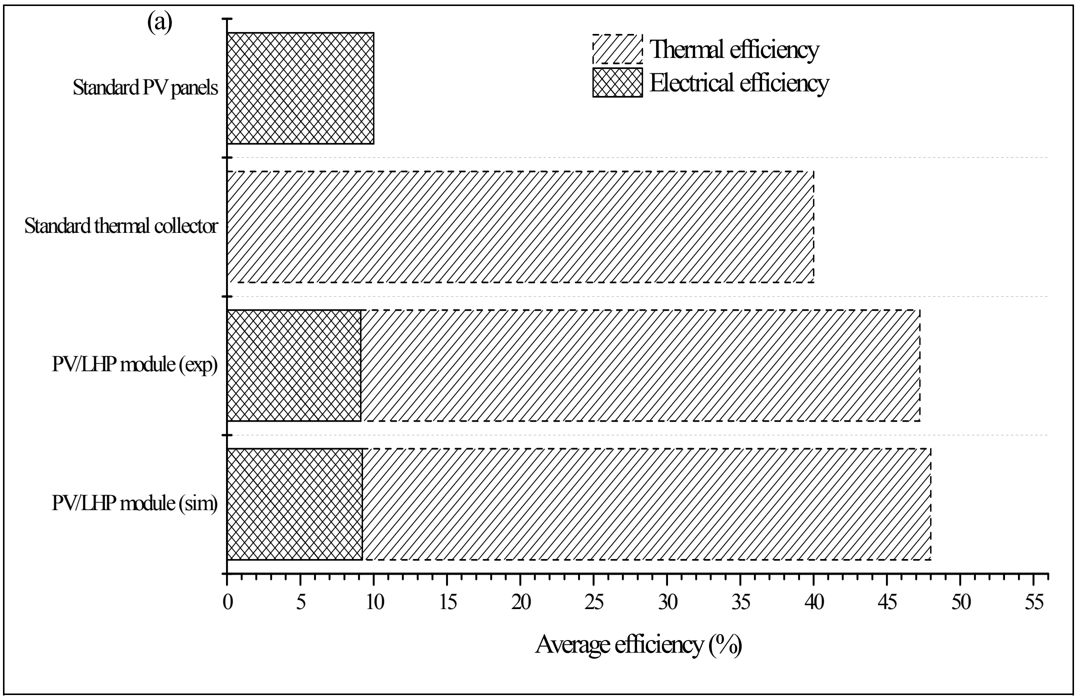
The minor discrepancy can be caused by both theoretical and measurement errors. For the theoretical analysis, some simplified assumptions and empirical formulas were made and utilized, such as inappropriate omissions of heat capacities of two EVA layers, ignorance of the isentropic efficiency of heat pump compressor, may be the potential reasons for error generation. During the measurement, the factors, like insufficient insulations, inaccurate instrument/sensors, may cause the deviation of testing figures from prediction.

Table 2: Daily average system performances

Results	*I (W)*	Q_e *(W)*	Q_{th} *(W)*	Q_w *(W)*	η_e *(%)*	η_{th} *(%)*	η_o *(%)*	*COP*	$COP_{PV/T}$
Experiment	*321.44*	*29.45*	*120.08*	*146.86*	*9.12*	*38.13*	*47.24*	*5.51*	*8.81*
Simulation		*29.91*	*122.87*	*148.11*	*9.23*	*38.76*	*47.99*	*5.88*	*9.28*
Error (RE)		*1.45%*	*5.20%*	*4.58%*	*1.45%*	*5.20%*	*4.00%*	*8.80%*	*9.00%*

4.6. Comparison between PV/LHP-HP system and conventional solar/air energy systems

Given above outdoor weather conditions, system geometry and operational parameters, the daily average modelling and testing results were put into comparison with the conventional solar/air energy systems, displayed in Fig.8. It was observed that the mean overall efficiency of the PV/LHP module was more than 47%, which was higher than the average operational values of the independent PV panels (around 10%-12% [Solardirect, 2012]) and standard solar thermal collectors (about 40% [Bigginhill, 2012]). The system performance indicators (*COP* and $COP_{PV/T}$) were receptively found nearly twice and fourfold of the conventional air-source heat pump water heating system (ASHP) [Wikipedia, 2012], whilst one-and-a-half times and twice over the integral-type solar-assisted heat pump system (ISAHP) [Huang et al., 2001].



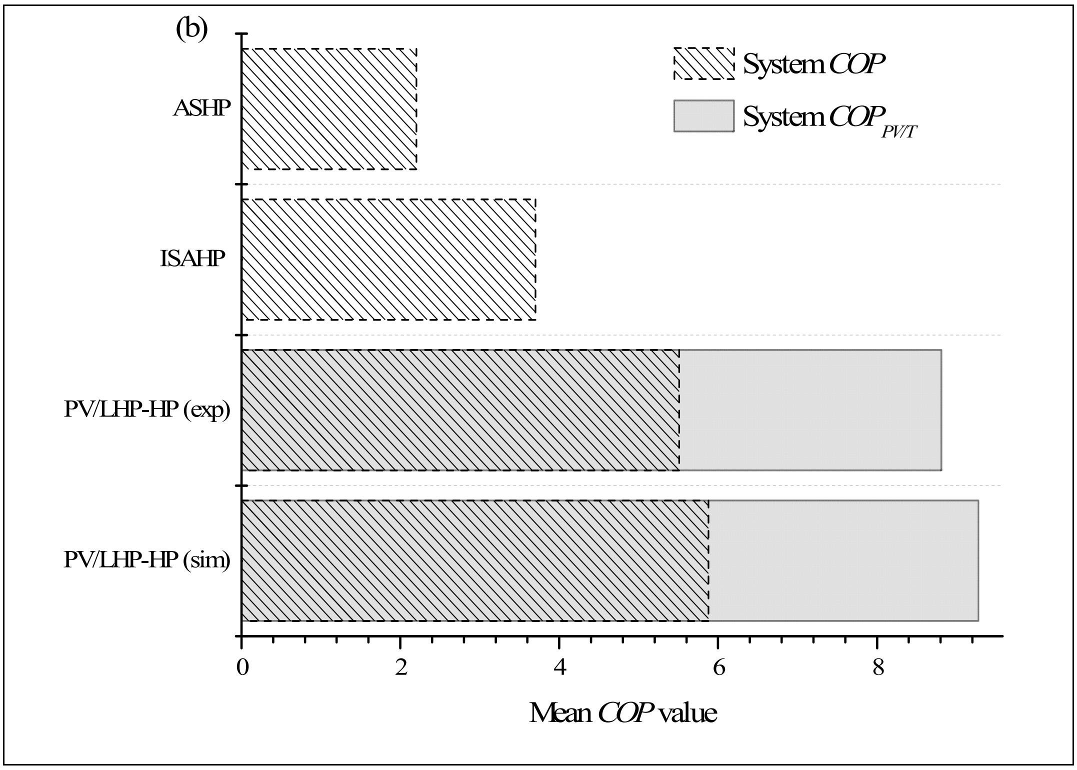


Fig. 8: Comparison between the PV/LHP-HP system and (a) independent PV panels, standard solar thermal collectors and (b) conventional air-source and solar-assisted heat pump water heating systems

5. Conclusion

This paper reported the daily dynamic performance of a novel solar photovoltaic/loop-heat-pipe heat pump water heating system, which has the potential to overcome some difficulties remaining in the existing PV/T technologies. A dedicated computer model was developed to predict the system performance depending upon heat balances mechanism. A prototype system was constructed and tested to examine its characteristic behaviors under practical outdoor weather conditions. Parallel comparison between the modelling and experimental results indicated that these two sets of data were in good agreement, and thus the established model was able to predict the system performance at a reasonable accuracy (mean error less than 9%). It was found that the average electrical/heat gain and efficiencies of the module were measured at around 29.45W/120.08W and 9.12%/38.13% respectively. For the system performance, testing results showed the average heat pump condensing capacity, values of *COP* and $COP_{PV/T}$, were at around 146.86W, 5.51 and 8.81 respectively. Error analysis was conducted from both the theoretical and experimental aspects. This hybrid technology enables the higher overall solar-energy conversion efficiency than the independent solar photovoltaic panel and solar thermal collector. The coefficients of system performance were nearly 1.5-4 times over the conventional solar/air heat pump water heating systems.

In overall, the research provided a dedicated method to determine the dynamic performance of such a new PV/LHP-HP system and gave some useful clues on further optimization of heat-pipe-type PV/T technologies and solar driven (space and hot water) heating systems, which would obviously contribute to realization of the energy saving and associated carbon emission targets set for buildings globally.

Nomenclature

A	*area (m^2)*
c	*Specific heat capacity (J/kg K)*
D	*diameter (m)*
h	*heat transfer coefficient (W/m K)*
h_m	*hour angle (rad)*
H	*thermal enthalpy (kJ/kg); height (m)*
I	*solar radiation (W/m^2)*
k	*thermal conductivity (W/m^2 K)*
K	*extinction coefficient of cover*
L	*length (m)*
L_m	*local latitude*
m	*mass flow rate (kg/s)*
M	*mass (kg)*
n	*mesh number*
n_g	*ratio of refraction index*
Nu	*Nusselt number*
q	*unit energy rate (W/m^2)*
Q	*energy rate (W)*
Pr	*Prandtl number*
R	*thermal resistance (K/W)*
Ra	*Rayleigh number*
Re	*Renault number*
T	*temperature (K)*
V	*velocity (m/s)*
W	*width (m)*
x	*width parameter*
x_r	*refrigerant saturation rate*

Greek

α	*absorption ratio*
β_p	*PV packing factor*
β_{PV}	*efficiency temperature coefficient*
$r_{\|\|}/r_{\perp}$	*parallel/perpendicular components of unpolarized radiation for surfaces*
δ	*thickness (m)*
δ_m	*declination angle (rad)*
ε	*emissivity; porosity*
η	*efficiency*
θ	*collector slop (degree)*
θ_1	*incidence angle (rad)*
θ_2	*angle of direct solar beam (rad)*
μ	*dynamic viscosity (kg/m s)*
ν	*kinematic viscosity (m^2/s)*
ρ	*density (kg/m^3)*
σ	*Stefan–Boltzman constant*
τ_c	*cover transmittance*
$\tau_{c,a}$	*transmittance due to absorption*

Subscripts

a	*air*
b	*backplane*
c	*cover; convection*
e	*electricity*
ei	*electrical insulation*
f	*fin sheet*
fc	*center of fin sheet*
fe	*edge of fin sheet*
fs	*insulation around fin sheet*
hp	*heat pipe*
hp,w	*heat pipe wall*
hx	*heat exchanger*
l	*liquid*
lf	*liquid film*
m	*mean, module*
p	*PV*
r	*refrigerant*
r,e	*refrigerant evaporator*
r,l	*liquid refrigerant*
rc	*reference temperature*
r,m	*mean refrigerant*
R	*radiation*
s	*solid*
th	*thermal*
o	*overall*
v,e	*vapour core in evaporator*
w	*water*
wi	*wick*
ws	*insulation of water tank*
ws,in	*inner tank insulation*
ws,o	*outer tank insulation*

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IZ-CON: an intelligent zone controller for building systems operation

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Abstract:
This paper describes the concept of an intelligent zone controller (IZ-CON) for integrated operation of building systems. IZ-CON is intended to deploy a predictive control methodology with embedded simulation capability. Thereby, the scalability problem of predictive simulation-assisted control method toward accommodating large and complex buildings is addressed. Moreover, the IZ-CON is inspired by a specific approach to building's control scheme involving the division of the target building into a number of well-formed sub-domains. Toward this end, a generative scheme for representation of buildings' systems control architecture is developed that allows for a structured distribution of systems' control logic. The scheme is cogently derived from a limited set of initial relationships between two entity layers. The first entity layer comprises of building zones subject to environmental control actions. The second layer comprises of technical devices responsible for control functionality. The entire control scheme – including the IZ-CON nodes – is derived in an automated fashion based on the relationships between the above two layers.

Keywords:
simulation-based building systems control, zone controller

1. Introduction

This paper describes the concept and structure of an intelligent zone controller (IZ-CON) for integrated operation of building systems. IZ-CON approach to building systems operation may be summarized as follows:

i) IZ-CON applies a predictive control methodology, which is powered with embedded simulation capability (Mahdavi 2008). In contrast to the majority of conventional control algorithms (e.g., rule-based methods, PID), the simulation-based control approach is proactive, rather than reactive. The simulation-based approach is also to be distinguished from the model-predictive control (Richalet et al. 1976, García et al. 1989), as it involves the explicit and run-time deployment of numeric simulation in the control logic. Previous work and associated small-scale implementations of the approach have been shown to be effective (Schuss et al. 2011). However, there are some doubts about its feasibility in terms of scalability toward accommodating large multi-zone buildings with multiple systems. We believe that the IZ-CON approach is well-suited to effectively address the scalability problem of predictive simulation-assisted control method.

ii) IZ-CON deployment is based on a specific approach to the generation of building's control scheme and, specifically, the division of the target building into a number of well-formed sub-domains. Toward this end, we have developed a generative scheme for representation of buildings' systems control architecture that allows for an integrated and structured (hierarchical and traceable) distribution of systems' control logic. The scheme is cogently derived from a limited set of initial relationships between two entity layers. The first entity layer comprises of building zones subject to environmental control actions. The second layer comprises of projected devices responsible for control functionality. Once sub-domains are defined in a consistent manner, a network of communicating yet independent zone controllers (IZ-CONs) can be assigned to them.

iii) IZ-CON involves user in the control process in a threefold manner: *a)* user behavior patterns and tendencies are used as the basis for corresponding predictive models; *b)* users are provided with zone state information pertaining to, for example, indoor climate (e.g., temperature, relative humidity, air quality) and positions of control devices such as luminaires, shades, and fans; *c)* users are provided with individual control possibilities, including the option to override the automated control regime.

The work on IZ-CON is motivated by certain inadequacies in current approaches to building systems control. We argue that the design methods of systems control architecture in buildings have not kept pace with the integration requirements of increasingly complex technologies for heating, cooling, ventilation, and lighting of buildings. Decisions regarding the environmental control systems' type and devices, the number and extent of control zones, as well as the type, number, and position of sensors neither follow a structured approach, nor reflect a traceable reasoning. Rather, such decisions seem to be frequently made on an ad hoc basis. Moreover, decision processes in one domain (e.g. thermal control systems) are rarely coordinated with other domains (e.g. visual control systems). Such lack of structure and integration is likely to cause inefficiencies in design and operation of buildings and their systems. Specifically, implementations of innovative (e.g. predictive) building systems control strategies may be hampered in part due to a lack of transparent and systematic representations of the buildings' systems control architecture. Classical literature on control theory does not address this problem (Mosca 1995, CIBSE 2000, Franklin et al. 2006, Unbehauen 2008). Previous – more pertinent – research work in this domain (Mahdavi 2001a, 2004, 2005, Mertz and Mahdavi 2003) has not affected the current state of practice. We thus need more research and development efforts in this area.

2. Basic terminology

There is a lack of a universally agreed-upon terminology in building systems control. Thus, to facilitate the present treatment, a few terms, definitions, and exemplary instances are adapted as per Table 1. Figure 1 illustrates a basic control loop: A device is assigned to control a certain parameter of a control zone. The controller (seat of the control algorithm) receives sensory information (S) concerning this parameter and manipulates the devices actuator (A). Consequently, the device delivers to (or extracts from) the control zone some amount of mass and/or energy via the device's terminal (T). The building systems control terminology of Table 1 is not free of inconsistencies and ambiguities. Nonetheless, it works fairly well, if certain conditions, qualifications, and simplifications are applied. Two such qualifications are briefly discussed below.

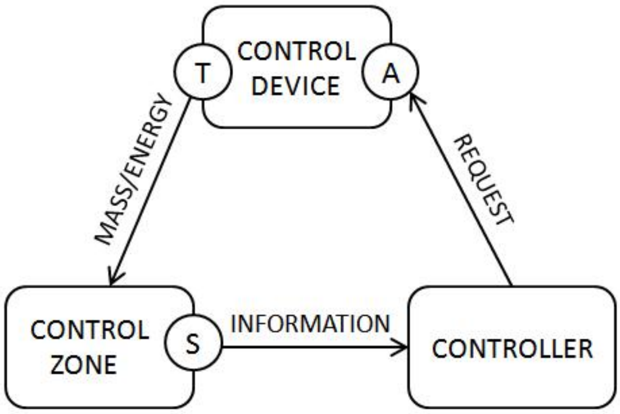

Figure 1. A basic control loop involving a control device, a control zone, and a controller. Here "T" and "A" denote device's terminal and actuator, whereas "S" stands for sensor.

Table 1. Selected terms for building systems control (based on Mahdavi 2001a, 2004, with modifications).

Term	Definition	Instance
Controller	Agent that sets control actions	People, software (algorithm)
Control action	Induced change in the state of a control device's actuator	Opening a window, switching lights on/off
Actuator	Component of a device that, acting upon a control command, brings about device state changes	Valve, dimmer, people
Control device	A technical element or system, whose purpose is to deliver to (or remove from) a control zone some quantity of mass and/or energy	Window, luminaire, HVAC
Control device terminal	The technical component of a control device that acts as its interface to the control zone	Radiator, diffuser
Control objective	To maintain a certain state in a control zone by keeping the respective control parameter in a certain range	Maintaining air temperature (or illuminance levels) in a control zone (a space, or a task plane) within a certain range
Control parameter	Indicator of the control zone's relevant state	Air temperature, relative humidity, carbon dioxide concentration, illuminance
Actuator state	Position of a control device's actuator	Open/close, dimming level, valve position
Control zone	Target domain of control action	Workstation, room, floor, building
Control state space	The logical space of all possible positions of all relevant actuators	All possible positions of windows, blinds, luminaires, etc.
Sensor	Reports the actual value of a control parameter in a control zone	Thermometer, photometer

First, the notion of a "control zone" needs to be properly understood. Recurrent miscommunications between control engineers and building design professionals could be avoided, if control zones are seen as the physical targets of control actions and not necessarily as architectural entities such as rooms. Perhaps it would be helpful to think of a control zone as a fluid (i.e., flexible) entity that can be projected to buildings' constituents spaces and elements, but it is not identical with those. To exemplify this point, Figure 2 illustrates the case of a simple open plan office space with multiple devices and multiple overlapping zones. In this case, the devices include external shade (B), windows (W1, W2), radiators (R1, R2), and luminaires (L1, L2). As the schematic depiction in this Figure demonstrates, the devices may have different and overlapping intended impact areas (control zones). Thus, zones may be associated with parts, whole, or aggregations of architectural spaces. Moreover, zones need not always imply three-dimensional volumes, but can refer to two-dimensional planes, as in the case of illuminance control on a horizontal task surface.

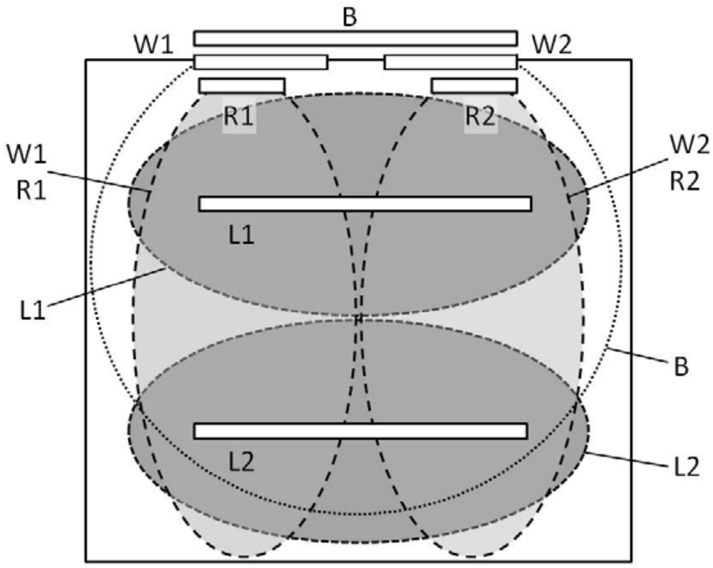

Figure 2. Illustrative depiction of a simple office space plan with multiple devices (B: external shade; W1, W2: windows, R1, R2: radiators; L1, L2: luminaires) and associated control zones.

Second, a control device (if the term is to cover entities such an HVAC system) is not necessarily a simple stand-alone technical component (such as window or luminaire) that has just one actuator with a simple set of distinct states. Rather, it is frequently a complex and nested (hierarchically organized) technical system. For example, a building's mechanical ventilation system consists of numerous components at multiple levels. Large amounts of conditioned air mass may be centrally prepared, distributed around the building over an extensive network of ducts, and finally delivered – via multiple terminals – to the building's multiple thermal zones. Terminals may in turn possess embedded, individually controllable, generative elements (such as reheat coils).

A simplification of this complexity would be beneficial for the purposes of the present discussion. Toward this end, we suggest to view a complex device in terms of a black box, whose virtual actuator is realized at the location of the device's terminal (i.e., its interface with the control zone). The assumption is that the complex device's machinery within the black box is controlled in a way such that, upon request (i.e., upon manipulation of the device's virtual actuator) modulated amounts of mass and/or energy would be released to (or extracted from) the target control zone. In other words, the control device in the present discussion can be regarded as a zone-specific terminal of an overarching nested system, which is represented in the proposed generative control schema through its virtual actuator.

3. A schema for the structured representation of the control logic

3.1. Defining the problem

The previous discussion allows us to pinpoint one of the primary sources of complexity in designing control systems for buildings. In most practical cases, there is no one-to-one mapping between devices and control zones. Rather, the control parameter (e.g., air temperature) in a target control zone (e.g., in a room) may be influenced – intentionally or unintentionally – by the operation of multiple devices such as windows, radiators, and shading elements. Likewise, the operation of a single device such as shading element may influence two or more distinct control parameters representing different control zones (e.g., indoor air temperature and task illuminance). In other words, devices and zones could maintain one-to-one, one-to-many, and many-to-one relationships. Thus, more often than not, the control task in a building must address a many-to-many pattern of relationships between control devices and control zones.

The problem can now be framed as follows. On the one hand, a decentralized distribution of control logic appears attractive in view of considerations pertaining to system robustness, scalability, flexibility, adaptability, and safety. On the other hand, the complex interplay of multiple devices in view of their implications for multiple control zones appears to imply a rather concentrated organization of control logic. In the extreme, where all devices can influence all zones, the control logic will have to be highly centralized. To address this problem, the present contribution reports on the recent developments regarding a previously introduced schema for the architecture of a building's systems control logic (Mahdavi 2004). This schema is primarily intended to support a systematic distribution of control logic in complex buildings.

We envision a simple generative schema is that allows for the high-level representation of a building's systems control logic. The starting point for schema generation is the unambiguous definition of two entity layers, namely control zones and control devices. Subsequently, the relationships between these layers must be established. A relationship denotes either a physical intervention involving mass and/or energy flows instantiated by the device controller and acting on the control zone, or zone state information flow via zone sensor to device controller. Note that the definition of two entity layers and their relationships involves some heuristically-based judgments and associated uncertainties. For instance, unintentional minor impact of a specific device such as heat emission of a luminaire on a specific zone state indicator such as air temperature may be neglected, as the purpose of a luminaire is not to heat a zone, but to illuminate it. Moreover, the assumed impact zone of a device and its actual impact area may be different: The impact regions of control devices can be rarely defined in terms of sharp boundaries. Computational methods to support the design task with these uncertainties are conceivable and partially under development. However, we shall not deal with them in the present treatment.

We suggest that the distributed architecture of the building systems' control can be derived cogently from the aforementioned limited set of initial relationships between two entity layers, control zones and control devices, in an automated rule-based fashion (Mahdavi 2001a, 2004, Mertz & Mahdavi 2003). This architecture can be seen as a template of distributed nodes, which can contain partial methods and algorithms for control decision making.

3.2. Generation rules

If a control task involves only one-to-one relationships between control devices and zones, the control logic architecture would be trivially distributed (maximally flat). At this basic level, every device can be thought as having a device controller (DC). The task of DC is to operate the Device's actuator autonomously, in the absence of higher-level requests. However, as previously argued, the real world building systems control tasks often involve many-to-many relationships. In the theoretical extreme case, where every one of p devices would influence every one of q zones, $p \times q$ relationships between devices and zones would have to be reckoned with. While real cases might not be nested as much, there is still a great deal of interdependency. Consequently, the design of a required complex control code structure could be supported, if it could be broken done into a manageable number of clearly defined segments or nodes. Generative rules could be applied to derive such nodes in the control schema for the accommodation of well-formed pieces of control logic in terms of rules, algorithms, and simulation code. We propose a set of such generative rules toward generating a multi-nodal control logic schema, i.e., a unique hierarchical multi-layered configuration of nodes for a specific control task:

- Step 1: Arrange distinct control zones as the basis layer of the schema. The state of these zones is captured via respective zone sensors.

- Step 2: Arrange device controllers (DCs) in the next layer. Every individually controllable device is assumed to have a DC with access to the Device's actuator.

- Step 3: Connect device controllers (DCs) to the zones, whose states are appreciably influenced by the operation of DCs.

- Step 4: generate the zone controllers' layer (IZ-CONs) as follows: if more than one DC influences the same zone, a respective zone controller is required to coordinate their operation. This layer accounts thus for the need for zone-specific coordination across multiple devices.

- Step 5: generate the high-level controllers (HC) layer as needed: If a DC receives requests from more than one zone controller, a high-level controller (HC) is generated. This layer accounts thus for the need for device-specific coordination across multiple zones.

- Step 6: If high-level controllers overlap in terms of devices involved, merge them into one meta-controller.

Such a schema may be generated for an entire building or any part of a building that may be regarded as closed (well-bounded) in terms of control actions and their implications.

3.3. An illustrative schema generation example

Consider the illustrative control task pertaining to a simple office space as depicted in Figure 3. Control objective is maintaining the values of a number of zone state indicators or control parameters within target values. These are in this case air temperature (θ), relative humidity (RH), carbon dioxide concentration (C), and illuminance (E_1, E_2),. The control task is to be accomplished via the operation of two windows (W1, W2), a shading device (B), two radiators (R1, R2), and two luminaires (L1, L2). Following the steps described in section 3.2, the distributed multi-layered multi-domain systems control schema of Figure 4 emerges. In this schema, layers 1 (zones) and 2 (device actuators) result from steps 1 to 3. Layers 3 (IZ-CONs) and 4 (high-level controllers) result from steps 4 and 5 respectively. Layer 5 (meta-controller) results from step 6. In this schema, the direction of control requests is downwards, whereas the sensor information flows upward.

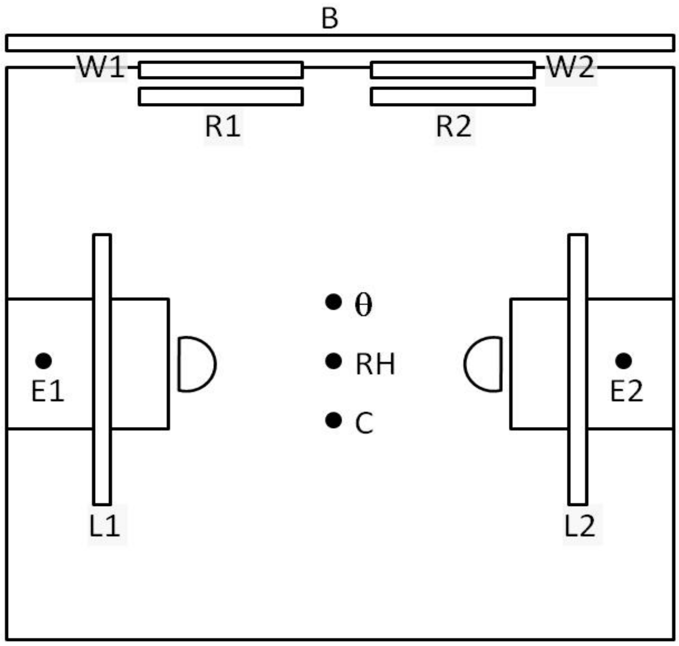

Figure 3. An office space with seven devices (windows W1 and W2, two radiators R1 and R2, two luminaires L1 and L2, and external shade B) and five sensors (illuminance sensors E1 and E2, indoor air temperature, relative humidity, and carbon dioxide sensors θ, RH, and C).

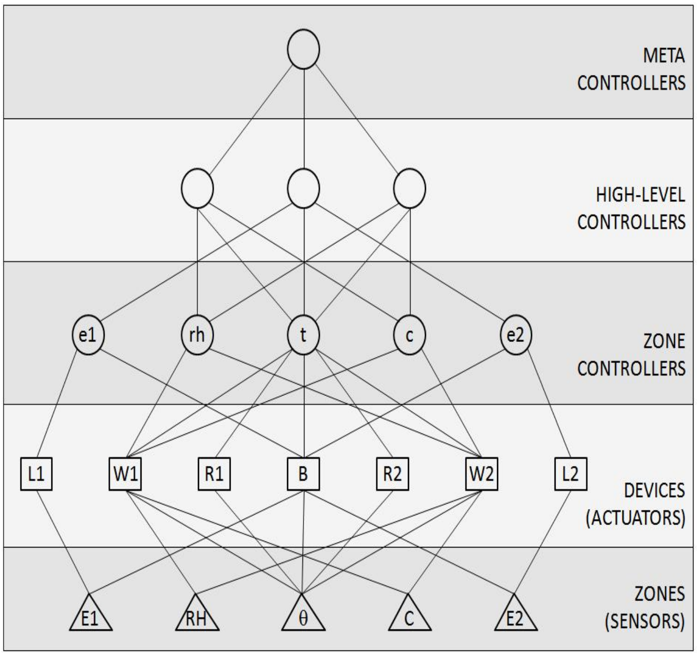

Figure 4. Illustrative distributed multi-layer multi-domain systems control schema for the office space of Figure 3.

3.4. Populating the schema with semantics

In the previous section, a process was described to generate schemata for building systems control. However, it is important to emphasize that the schema does not predetermine what kind of control method or style is applied at each instance. Rather, the nodes in this schema represent containers or place-holders for pertinent parts (code segments) of the overall control logic. Consequently, the nodes can accommodate a variety of rule-based and/or algorithmic control solutions. A crucial benefit of the schema can be seen in its potential to provide a structured platform for a modular and distributed assembly of control code for large and complex building systems operation scenarios. The manner in which the schema could be populated with control semantic could be further discussed with reference to the promising option of a simulation-based control strategy (Mahdavi 1997, 2001b, 2008). According to this strategy, control decisions are made upon evaluation of the computed implications of virtually enacted control options. This implies that at each control decision making instance, available control options, i.e., the alternative actuator positions, are virtually realized via simulation. The simulation results, which are the projected values of the control parameter for a specific point of time in future, are then compared to identify the most promising option. Thus framed, the control task can be seen as navigation of the control state space. In case of multiple devices with a large number of possible states, the computational handling of the control state space may become infeasible. A circumstance that is further aggravated due to the necessity to conduct such computations on a recurrent basis: The control process is of course a dynamic one, given the changing nature of relevant boundary conditions such as weather, occupancy, as well as user preferences and priorities. Hence, the optimal combination of device actuator positions must be arrived at in an ongoing manner. To reduce the size of the control state space, various methods from operation research and optimization can be applied (Mahdavi 2008, Schuss et al. 2011).

To semantically populate the proposed generic system, the simulation-based control strategy could make good use of the nodal structure. Devices can be equipped with simple methods to either autonomously operate their actuators (for instance in case system communications break down), or to suggest, to the upper layers, preferable actuator positions. IZ-CONs could merge the recommendations they receive by comparing the advantages of operating one device versus another. Alternatively, they could use partial system models to predict, compare, and evaluate the performance implications of recommendations from the lower layer. Similarly, meta-controllers could evaluate submitted options via some performance criteria (e.g., the pertinent devices' energy use), or they could independently conduct whole system simulations for all or a part of the recommendations they receive.

An attractive feature of the proposed schema is its capability to flexibly accommodate multiple evaluation criteria toward optimal control decision making. Thereby, evaluation criteria can be represented not only in terms of real sensors but also in terms of calculated, derived, simulated, aggregated, and virtual sensors. For example, performance indicators such as mean radiant temperature, PMV (predicted mean vote), and various glare indices could be computed real-time and the results could be reported by the sensors to the higher levels of systems control hierarchy. Likewise, environmental performance criteria such as CO2 emissions attributable to consumption of a certain type of fuel as well as economical performance indicators such as energy-related expenditures could be effectively accommodated in the schema in terms of corresponding virtual sensors.

3.5. A prototypical implementation instance

Currently, an actual implementation of the proposed IZ-CON approach is being prepared within the framework of the EU-supported CAMPUS 21 project (CAMPUS 2011). Toward this end, the Environmental Research Institute (ERI) Building of the University Collage Cork (UCC) is selected. An open office space in this building will be used for the prototypical implantation. The ERI Building (Figure 4) has an up to date building automation system and a fairly comprehensive monitoring infrastructure. The selected south-facing space (Figure 5) is located in the first floor (Figure 6).

Figure 4. The ERI Building.

Figure 5. Selected open office space.

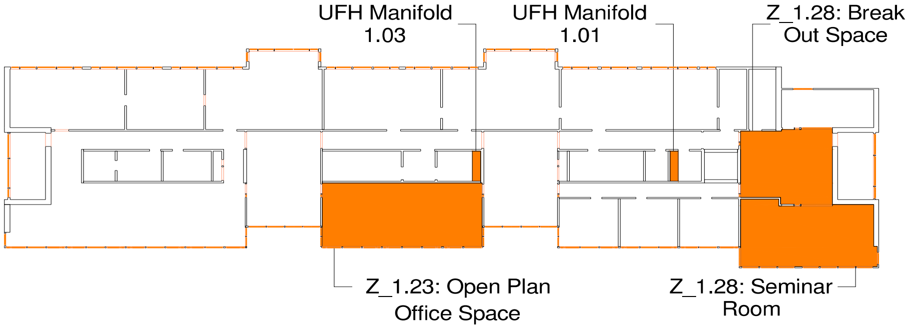

Figure 6. ERI Floor plan with demonstration room Z_1.23

The documentation of the original control setup does not reveal an explicit analysis of the complex relationships between devices, actuators, zones, and sensors. The first step in the implementation of the control task is thus to capture and represent such relationship. As the schematic representation in Figure 7 shows, the space has the following individually controllable devices: 4 blinds (B1 to B4), 4 operable windows (W1 to W4), and 4 sets of 2 luminaires (L1A/L1B to L4A/L4B). Moreover, the space is supplied with a constant volume air system (V) and a floor heating system (H). The control objective is maintaining the values of a number of zone state indicators or control parameters within target values. In this case, the control scheme is based on the assumption of 4 lighting zones (represented by illuminance sensors E1 to E4), and two compound hygro-thermal and indoor quality zones represented by two sets of sensors for air temperature, relative humidity, and carbon dioxide concentration (θ1, RH1, C1 and θ2, RH2, C2). Following the steps described in section 3.2, the distributed multi-layered multi-domain systems control schema of Figure 8 emerges. In this schema, layers 1 (zones) and 2 (device actuators) result from steps 1 to 3. Layers 3 (IZ-CONs) and 4 (high-level controllers) result from steps 4 and 5 respectively. Layer 5 (meta-controller) results from step 6. Note that, for simplification purposes, secondary (relatively less essential) device influences on zones (dotted lines in Figure 8) were neglected in the scheme generation process. Hence, the resulting schema consist one meta controller for the coordination of the two high level controllers from the two hygro-thermal and air quality zones.

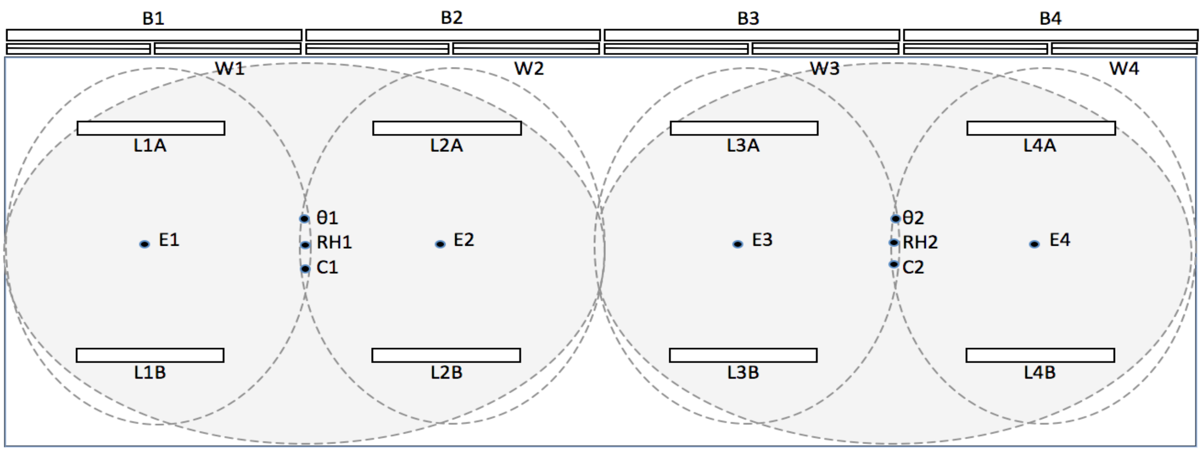

Figure 7. The ERI office space (Z_1.23) with devices (windows W1 to W4, luminaires L1 to L4, and external shade B1 to B4) and ten sensors (illuminance sensors E1 to E4, indoor air temperature θ1 and θ2, relative humidity RH1 and RH2, and carbon dioxide sensors C1 and C2).

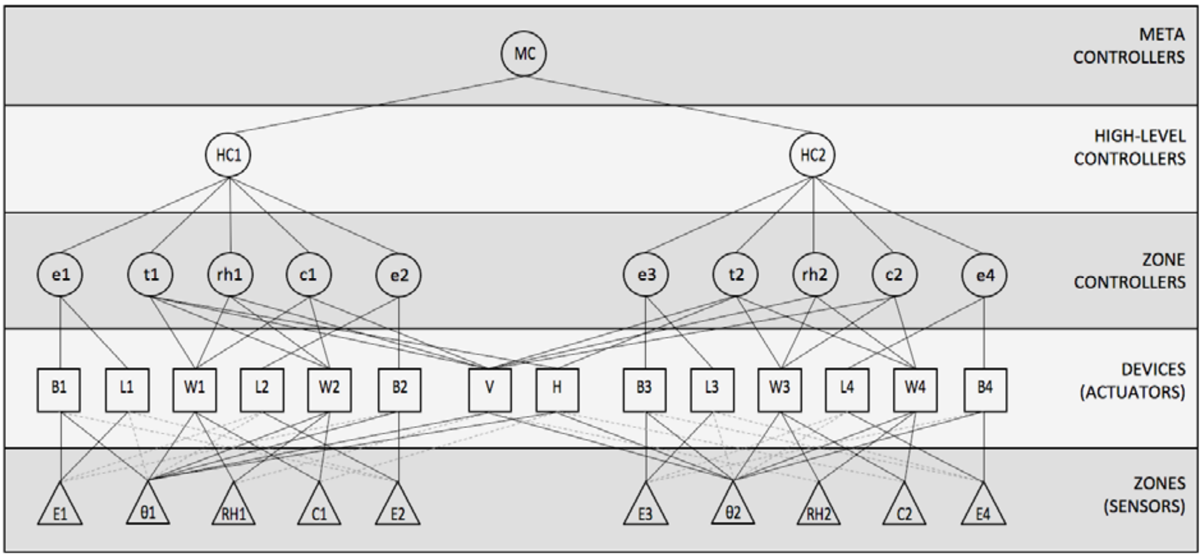

Figure 8. Illustrative distributed multi-layer multi-domain systems control schema for the open office space (Figure 7).

4. conclusion

This contribution described a method to generate a schema for the control architecture of multi-zonal multi-domain building systems control scenarios. The schema allows breaking down a complex control task into five layers (zones, devices, IZ-CONs, high-level controllers, and meta-controller). IZ-CONs facilitate zone-specific coordination of multiple devices. Nodes in the high-level controller layer facilitate device-specific coordination across multiple zones. These nodes provide thus containers for the distributed encapsulation of the building systems control semantic. An illustrative real-world instance of the schema deployment was presented.

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Evidence-based calibration of a building energy simulation model: Application to an office building in Belgium

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Abstract:

Energy services play a growing role in the control of energy consumption and the improvement of energy efficiency in non-residential buildings. This work consists in the application of a simulation-based approach dedicated to whole-building energy use analysis for use in the frame of an energy efficiency service process. Focus is given to the calibration of a simplified dynamic hourly building energy simulation model by means of available energy use data and to the integration of the calibration process into the Energy Service Process. The developed simulation tool and the associated calibration method are applied to a real case study building located in Brussels, Belgium. The use of an evidence-based method ensures sticking to reality and avoids bad representation and hazardous adjustment of the parameters. Moreover, it is shown that the use of a sensitivity analysis method is of a great help to orient data collection and parameters adjustment processes.

Keywords:

Building energy services, energy use analysis, calibration, modeling, simulation

1. Introduction

Environmental concerns and the recent increase of energy costs open the door to innovative techniques to reduce energy consumptions. Buildings represent about 40% of the European energy consumption (Perez-Lombard, 2008). Non-residential buildings are part of the main energy consumers and improvement of their energy performance is a major challenge of the 21th century. To this end the European Commission approved the European Directive on Energy Performance of Buildings (EPBD, 2002) on 16 December 2002. In 2006, the European Commission approved a second directive (Directive 2006/32/EC) promoting the development of a market for energy services in the member states in order to improve the energy efficiency in the building sector and support the energy demand management.

EN15900 describes Energy Efficiency Services (EES) as a process based on collected energy use data, designed to achieve an energy efficiency improvement and including a series of steps such as: (1) Energy audit or inspection, (2) Measurement and verification of implemented Energy efficiency improvement action(s) and (3) Periodic verification of the energy performance of the building and continuous operation optimization.

Most of the steps of the energy efficiency service process require on-field measurements and energy use analysis. Today, while detailed on-field measurements and energy counting stay generally expensive and time-consuming, energy simulations are increasingly cheaper due to the continuous improvement of computer speed.

Performance verification protocols (IPMVP, ASHRAE 14…) encourage the use of simulation models to evaluate the energy performance of existing buildings provided they are able to represent the actual situation with an acceptable accuracy. The fitting of a BES model to an existing situation involves using as-built information, survey observations and short and/or long term monitoring data to iteratively adjust the parameters of the BES model. This process is generally known as "calibration".

Ahmad and Culp (2006) have developed a blind time-limited test protocol to evaluate the range of discrepancies encountered when using uncalibrated simulations (between 30% and 90% when predicting total or specific energy usages) and shown that it is not possible to trust uncalibrated simulation models when studying an existing situation.

In the present paper, the development and the calibration of a simplified dynamic hourly building energy simulation model by means of available energy use data are presented. The proposed evidence-based calibration methodology is deeply related to on-field inspection and data collection issues and is developed to fit with the audit/inspection process. The developed simulation tool and the associated calibration method are applied to a real case study building located in Brussels, Belgium.

2. Simulation Tool and Calibration Methodology

2.1. Simple dynamic hourly simulation model

The calibration of a simulation model to an existing situation is usually a highly underdetermined problem. Indeed, only very scarce and limited information are usually available about the building (e.g. as-built files) and its performance (e.g. monthly energy billing data) while the number of parameters to adjust is generally high.

Popular commercial building energy simulation software's do not generally suit to the study of existing situations. Most of these simulation packages have been developed to support the design of new buildings and often include numerous details and aspects that cannot be investigated in practice. A simplified building energy simulation model has been designed and developed so as to fit with the requirements of whole-building energy use analysis (i.e. prediction of hourly heating and cooling needs and subsequent final energy consumptions) while minimizing the amount of parameters to adjust (Bertagnolio et al., 2010).

The quasi-steady state hourly simulation program developed in this work is based on the LSPE (loads - secondary system - primary system - economics) sequential approach (Reddy and Maor, 2006) and relies on simple normative models (e.g. ISO13790 simple dynamic hourly building model). The heating, cooling and latent loads computed by the building zone model are summed and converted into system loads and then, into final energy consumptions (Fig.1). This approach allows minimizing the number of iterations needed to simulate the performance of the building and its system.

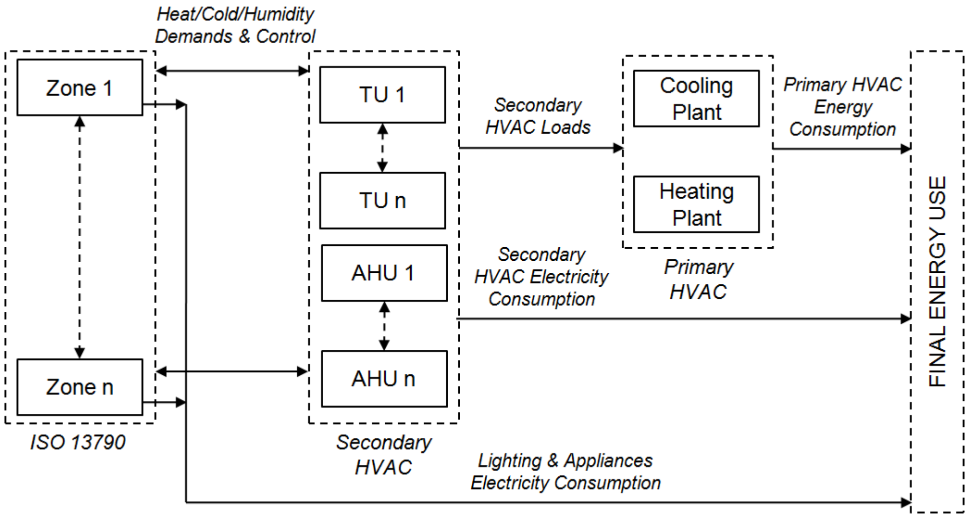

Fig. 1. Global building-HVAC model block diagram

When compared to reference detailed building simulation models (e.g. Trnsys, EnergyPlus…), the simplified model demonstrated an accuracy of less than 8% when predicting annual heating and cooling needs (Bertagnolio, 2012).

2.2. Evidence-based calibration method

The calibration of a forward building energy simulation model remains a complex and highly underdetermined problem. In other words, even if the "net effect" of all the "knobs" may yield to a simulated output close to the measured one, there is no guarantee that all individual "knobs" are properly tuned. Even if a special attention has been paid to select easily identifiable parameters with a physical meaning, the number of parameters to calibrate remains important in comparison with the very limited amount of available data (e.g. monthly energy bills).

Because of the complexity of the problem, the four following issues are considered as crucial when performing a calibration:

- Reproducibility and robustness, ensuring the method is systematic and may be applied to numerous cases;
- Sensitivity issues, consisting in distinguishing influential and non-influential parameters;
- Uncertainty issues, consisting in characterizing or quantifying the final uncertainty on the model's outputs;
- Accuracy issues, related to the definition of the calibration criterion that will be used to estimate the quality of the calibrated model.

In the present work, a systematic evidence-based calibration method making intensive use of sensitivity and (non-intrusive) measurement issues is developed (Fig. 2). The calibration work starts by setting up the initial as-built input file based on available information (architectural plans, as-built files, technical sheets…). Generally, this first simulation run provides results with an accuracy of about 30% (Ahmad and Culp, 2006) in terms of annual energy use. This as-built input file is then used as a basis for the sensitivity analysis phase. Indeed, the parameters of the model are characterized by "best-guess" values (i.e. the best approximation of the parameter based on the available information) and "uncertainty ranges" expressing the doubts about the considered values.

The next steps of the calibration methodology relies on the definition of two types of hierarchy:

- A hierarchy between influential and non-influential parameters: sensitivity analysis is used (1) to distinguish influential and non-influential parameters (non-influential parameters are then fixed to their best-guess value following a factor fixing approach) and (2) to classify the influential parameters by order of importance (screening) in order to orient on-site data collection work;
- A hierarchy between the sources of information exploited to identify the parameters: Priority is given to physical observation and measurements. Adjustment of a parameter is done only if the value consists in an "improvement" of the quality/reliability of the model (i.e. the updated value has a physical meaning and has been obtained from a more reliable source of information, e.g. direct measurement, than the previous one, e.g. on-site observation).

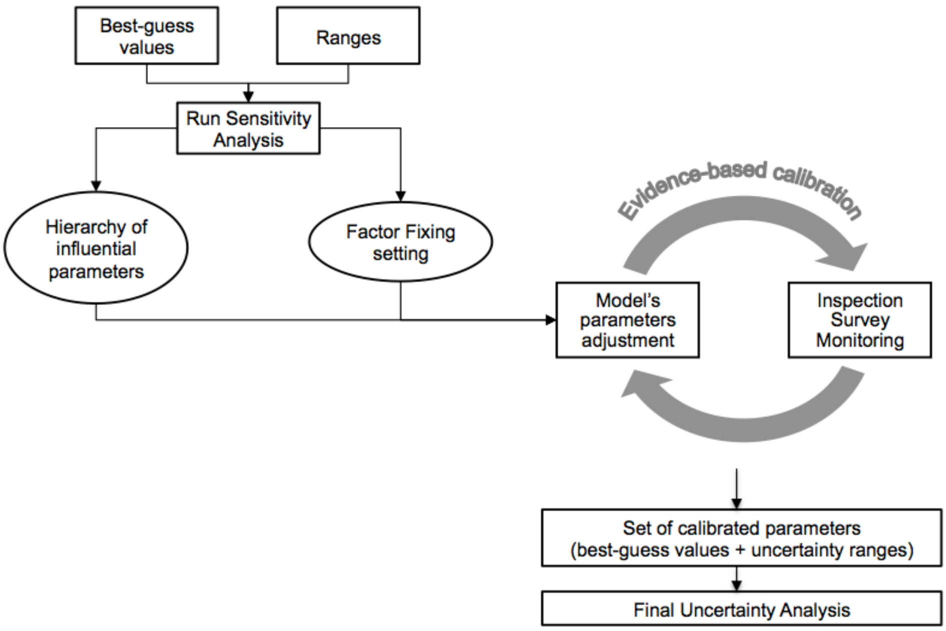

Fig. 2. Evidence-Based Calibration Methodology

Even if the model is not highly non-linear, the interaction effects have to be characterized in order to provide good guidance for calibration and a global sensitivity method has to be used. The Morris' sensitivity analysis method (1991) is used to identify and hierarchize the most influential parameters of the model. This method was found to be suitable for application to BES models by De Wit (1997) since it is not dependent on the properties of the model and does not require any assumption regarding linearity or correlations between the inputs and the outputs of the model.

Heiselberg and Brohus (2007) also highlighted other advantages for the Morris method:

- The method can handle large number of parameters and requires a relatively limited amount of simulation runs;

- The parameters are varied globally within the range and the whole parametric space can be explored without pre-defining the probability density function of each parameter;
- The results are easily interpreted and visualized graphically as prescribed by Morris (1991).

The sensitivity of the output is characterized by a value called "Elementary Effect". The effect of a given parameter is calculated several times, at randomly selected points of the parametric space. The mean value of the effect is then compared to the dispersion (standard deviation) in order to allow the selection of the most influential parameters and the distinction of parameters with linear effects from parameters with nonlinear effects (i.e. interactions).

In the other hand, the Morris analysis does not allow uncertainty analysis because it does not take the shape of the probability density function of the parameters into account (De Wit et al., 2002). Indeed, the method cannot be considered as quantitative. The value of its measures can only be used to rank the studied parameters by order of influence and characterize the structure of the model but cannot be interpreted as percentages of the output variance.

After having been identified as an influential parameter, the value of the concerned parameter has to be refined and the uncertainty range on this parameter can be narrowed. If practically feasible, spot (SpotM) or short-term (STeM) monitoring has to be considered in priority in order to allow direct quantification of the parameter. If redundant data are collected, the "higher quality" information (i.e. the information judged as the most representative of the usual operation/behavior of the building) should be used to specify the best-guess value of the parameter. The other values should not be neglected and can be used for crosschecking. If the physical measurement is not possible for a given reason (e.g. because of money or time constraints), it is suggested to consider the next parameter by order of influence. Proceeding in such a way ensures that the procedure is "evidence-based" and that priority is given to physical measurement and not to highly questionable or hazardous "tuning" of the parameter.

Specifying (and narrowing) probability/uncertainty ranges for the parameters all along the calibration allows characterizing the quality of the calibrated model at each step of the process (since specified ranges "express" the quality of the information used to adjust the parameter). At the end of the process, when the calibration criteria have been satisfied and all the critical issues have been tackled through of the available means, an uncertainty analysis is run to quantify the final uncertainty on the model's output following the Latin Hypercube Monte Carlo sampling method.

2.3. Calibration Accuracy

Several authors have studied the question of the definition of a criterion to assess the quality of calibration. It appeared that it is delicate (if not impossible) to define a general criterion, ensuring proper calibration of a given simulation model to a given existing situation. Usually, statistical indexes (MBE: Mean Bias Error and CVRMSE: Coefficient of Variation of the Root Mean Square Error) computed on annual or monthly basis (as prescribed by ASHRAE, 2002) are used as calibration criteria. However, such criteria are often considered as too cool or not representative enough of the quality of the calibrated model. In addition to this mathematical criterion, it is suggested to consider the following points to check the validity of the calibration:

- Computed peak heating and cooling loads have to be in good accordance with the installed heating/cooling capacities;
- If available, the recorded whole-building hourly electricity load should be compared to the computed values;
- Simulated daily/hourly energy use profiles (concerning internal gains, system operation, chiller load...) should be visually checked, criticized and confronted to the operating patterns observed (or measured) during the inspection phase.

3. Case Study

The main results of the application of the developed tools and methods to an existing office building located in Bruxelles (Belgium, Fig. 3) are summarized below. The building was built in the 70's and was largely refurbished in 1998 (complete modification of the HVAC system and a renovation of the facade and of the indoor space). The building is characterized by an annual primary energy consumption of about 316 kWh/m²/yr (slightly below the average for similar buildings in Brussels).

Fig. 3. Case Study Building (SW façade)

The net floor area of the building is about 10100 m² and is distributed over 9 floors and includes mainly office cells and meeting rooms. The ground floor mainly includes the entrance hall, a library, some meeting rooms and offices. Levels +1 to +8 mainly include office cells. At each level, the core zone is split in two parts and has a similar composition and includes some utility areas (stairs, elevators, sanitary, storage, kitchen, copy rooms…). The three basement levels (about 2534 m² each) mainly include parking areas.

Five main Air Handling Units (AHUs) serve the three main conditioned zones of the building:

- AHUs #1 and #2: The offices located at Levels +1 to +8
- AHUs #3 and #4: The ground floor peripheral zones (meeting zones, offices and library)
- AHU #5: The Entrance hall

AHUs #1 and #2 are Constant Air Volume (CAV) units and include adiabatic humidification systems. A fraction of the air extracted by these two units is sent back to the parking levels -1 and -3. The AHUs #3 and #4 are Variable Air Volume (VAV) units and serve the peripheral zones located at the ground floor. The fifth AHU (#5), serving the entrance hall, consists in a small ventilation unit supplied with vitiated air extracted from the zone and a small fraction of fresh air coming from the AHU3. Four smaller ventilation units supply or extract air to/from auxiliary zones (parking, sanitaries, printshop…).

The peripheral zones located at the ground floor are equipped with VAV boxes controlling the supply airflow rate. Hot water convectors are installed all along the external walls (one per 2.4m of façade) to provide local heating to the peripheral zones. Cooling of the zones is ensured by increasing the supply airflow. Peripheral zones at levels +1 to +8 are equipped with vertical concealed 4-pipes heating/cooling fan coil units (one per façade module of 1.2m width).

Three natural gas boilers of 465 kW each ensure hot water production. Two classical boilers (#1 and #2) provide hot water to the AHUs heating coils and to the two air heaters located in the parking space. The third boiler is a condensing boiler and provides hot water to all the FCUs installed in the office zones (levels +1 to +8).

Chilled water production is ensured by two water-cooled chillers of 512.4 kW of cooling capacity each (rating EER: 4.27). Two indirect contact cooling towers equipped with two speeds fans ensure the cooling on the condenser side.

Monthly energy billing data, including natural gas, peak-hours electricity and off-peak-hours electricity consumptions, are available for 2008, 2009 and 2010. Whole-building quarter-hour peak electricity demand (in kW) is also available for these three years.

4. Calibration of the BES model

Four calibration levels can be identified when constructing the model (Table 1):

- Level 1: as-built input file
- Level 2: inspection level (consisting in visits of the building and installation, survey of installed equipment and analysis of the Building Energy Management System)
- Level 3: monitoring level (using spot and short-term monitoring)
- Level 4: questionnaire-based occupancy survey

At each calibration level, both statistical criteria and visual verifications are used to analyze the accuracy of the calibrated model and point out the issues that should have been investigated in order to continue improving the model.

Table 1: Calibration levels and data availability

<table>
<tr><th colspan="2" rowspan="2">Calibration levels</th><th colspan="6">Building description and performance data available for calibration</th></tr>
<tr><th>Utility bills[1]</th><th>WBE demand[2]</th><th>As-built data</th><th>Inspection</th><th>Spot/Short-term monitoring</th><th>Occupancy survey</th></tr>
<tr><td rowspan="6">Evidence-based process</td><td>Level 1</td><td>x</td><td>x</td><td>x</td><td></td><td></td><td></td></tr>
<tr><td colspan="7">Preliminary Sensitivity Analysis</td></tr>
<tr><td>Level 2</td><td>x</td><td>x</td><td>x</td><td>x</td><td></td><td></td></tr>
<tr><td>Level 3</td><td>x</td><td>x</td><td>x</td><td>x</td><td>x</td><td></td></tr>
<tr><td>Level 4</td><td>x</td><td>x</td><td>x</td><td>x</td><td>x</td><td>x</td></tr>
<tr><td colspan="7">Final simulation results and uncertainty on the predicted energy use</td></tr>
</table>

[1] Natural gas, peak-hours and off-peak-hours electricity consumption (in kWh) provided on a monthly basis
[2] WBE (Whole-Building Electricity) demand (in W) provided by the electricity provided on a quarter-hour basis

4.1. Level 1: as-built input file and preliminary Sensitivity Analysis (SA)

The initial input file is built based on the as-built information (complete description of building geometry, envelope and HVAC system using as-built and design information) but does not represent actual building use or operation and includes default values for lighting and appliances densities and schedules, as well as HVAC system setpoints and schedules.In order to reduce computation cost and parameterization work, similar zones and HVAC system components have been consolidated (e.g. consolidation of AHUs 1&2 and 3&4, two by two) following the rules proposed by Liu et al. (2004).

In addition to the so-called "best-guess" values, probability ranges have also been defined for each parameter of the model based on the (qualitative) uncertainty related to the source of the information in order to allow running uncertainty and sensitivity analyses. At this stage, conservative hypotheses have been made in order to define relatively large uncertainty ranges.

Table 2: Initial values and uncertainty ranges for some parameters

$IGFR_{light}$	W/m²	Lighting power density – Offices/meeting	12	-50%	+50%
$IGFR_{appl}$	W/m²	Appliances power density – Offices	10	-50%	+50%
$T_{i,set,h,occ}$	°C	Heating setpoint – Offices	21°C	-2°C	+2°C
$T_{i,set,h,nocc}$	°C	Heating setpoint (night) – Office	15°C	-2°C	+2°C
$T_{i,set,c,\ occ}$	°C	Cooling setpoint – Offices	25°C	-2°C	+2°C

For example, at this level, no information is available regarding the building use and operation. So, internal gains and corresponding schedules are set to default/typical values given in the literature (12 or 10 W/m^2) and characterized by large probability ranges (+/-50%). The same rule is used for internal temperature setpoints and HVAC system operation (Table 2). On the contrary, parameters known with a higher confidence are characterized by smaller intervals (e.g. envelope characteristics).

The defined set of values and ranges are used to generate a Morris sample for sensitivity analysis purposes. Relative influences of the parameters have been expressed in terms of impact on seasonal final electricity and natural gas consumptions. Impact on hot water and chilled water demands have also been studied in order to ensure a right representation of heating and cooling needs of the building by the calibrated model. Indeed, as shown in a previous study (Bertagnolio, 2012), even if gas consumption and heating needs are directly correlated, the relationship between cooling needs and electricity consumption is generally less direct. Hierarchy between most influential parameters is given in Table 3.

Table 3: Influential parameters hierarchized by order of influence

Parameter	Solar shading use	Supply T° setpoints	HVAC schedules	Heating Cooling setpoints	Occupancy schedules	Internal loads schedules	Internal loads densities	Ventilation rate
Influence								

These results are used to guide the data collection process (sort of “experimental design”) during the next steps of the calibration process. As the calibration progresses, collected data can be used to:

- Update the value of the given parameter if the new information is more reliable than the previous one (e.g. physical measurements vs default value; short-term monitoring vs BEMS recordings);
- (Cross)check the current value of the parameter if the quality level of the new information is lower (e.g. observation vs measurement; spot vs short-term monitoring data) or similar (e.g. spot monitoring performed at different moments).

As expected, the model based on the as-built input file is not reliable and consumption and demand profiles are badly predicted by the model. Moreover, the uncertainty on predicted electricity consumption disaggregation (quantification of relative consumption of main end-users) remains important (Fig. 4).

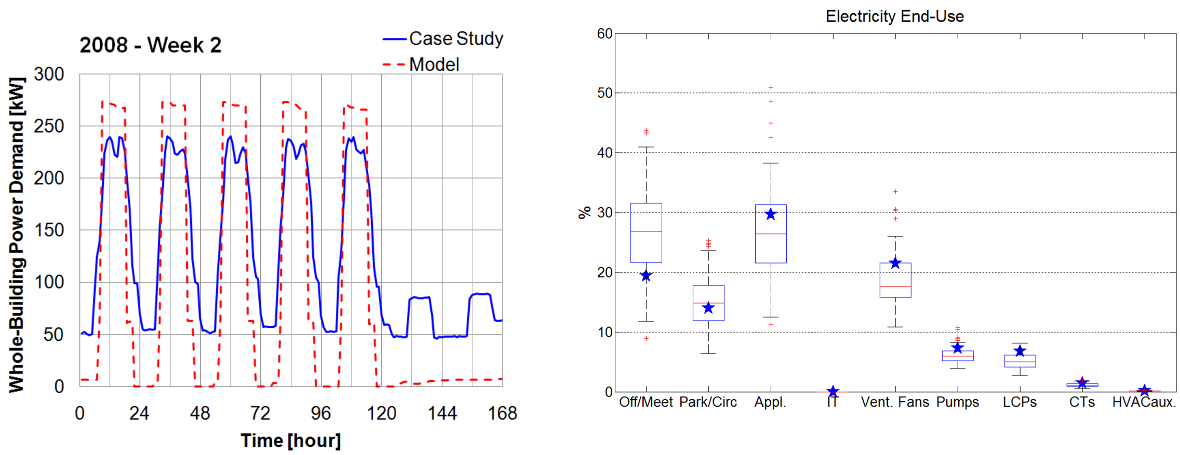

Fig. 4. Predicted vs Recorded WBE demand (in kW) for a winter week (left); uncertainty on predicted end-use electricity consumptions computed following the LHMC approach (right).

4.2. Levels 2, 3 and 4: Inspection, Monitoring and Survey

At the inspection level and monitoring level, data collection is oriented by the results of the preliminary sensitivity analysis described above and focuses on building use (occupancy, lighting and appliances use) and operation (HVAC system setpoints and schedules).

The inspection allowed collecting additional information about the actual operation of the HVAC system (setpoints, schedules) and making a survey of the installed lighting and appliances powers. At the end of this inspection, the model was updated (and the uncertainty ranges of the concerned parameters were narrowed). The global quality of the model was improved but some shadow areas remain (e.g. occupancy and operation schedules…).

Following the inspection, a monitoring campaign was launched. Once again, focus was given to parameters identified as influential and important for calibration and measurements were implemented in order to:

- Improve the knowledge about actually achieved levels of temperature and humidity in the zones (by using local temperature and humidity sensors);

- Identify actual occupancy, lighting use and appliances use patterns (by means power demand monitoring at zone and floor level, Fig.5);
- Confirm/Check the values of some HVAC system components performance, setpoints and schedules (by means of power demand monitoring on different electrical boards).

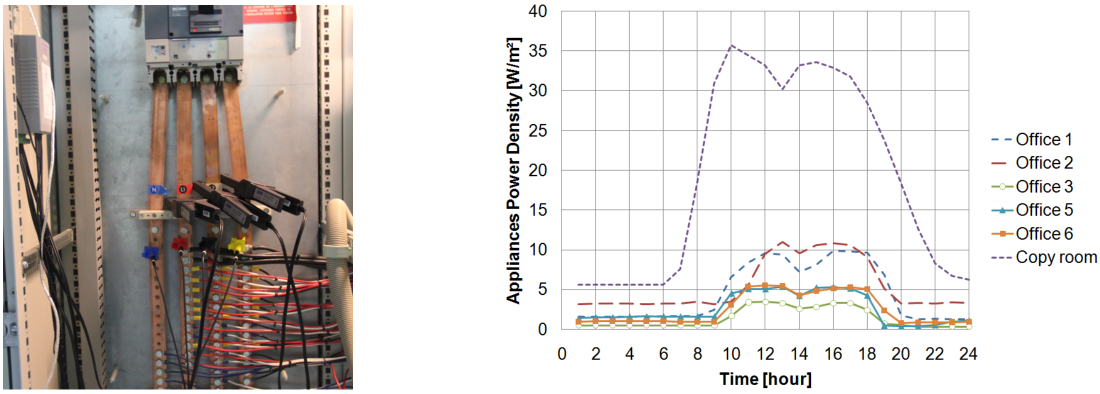

Fig. 5. Calibration Level 3: Installed electrical power logging device (left); Appliance power demand in several rooms for a typical day (right).

Because most of the measurements were done during winter, no information was available about the operation of the building during summer period. The last level of calibration included some information collected by means of a questionnaire sent to the occupants in order to characterize the level of occupancy (and activity) during summer holidays.

4.3. Finals Results

At the end of the 4th level of calibration, the model seems to be able to represent the actual energy behavior of the building with an acceptable accuracy. Monthly consumption profiles and sub-hourly power demand profiles are well represented (Fig. 6). Statistical indexes (MBE and CV(RMSE)) are also relatively low and satisfy the accuracy criteria specified by ASHRAE (2002).

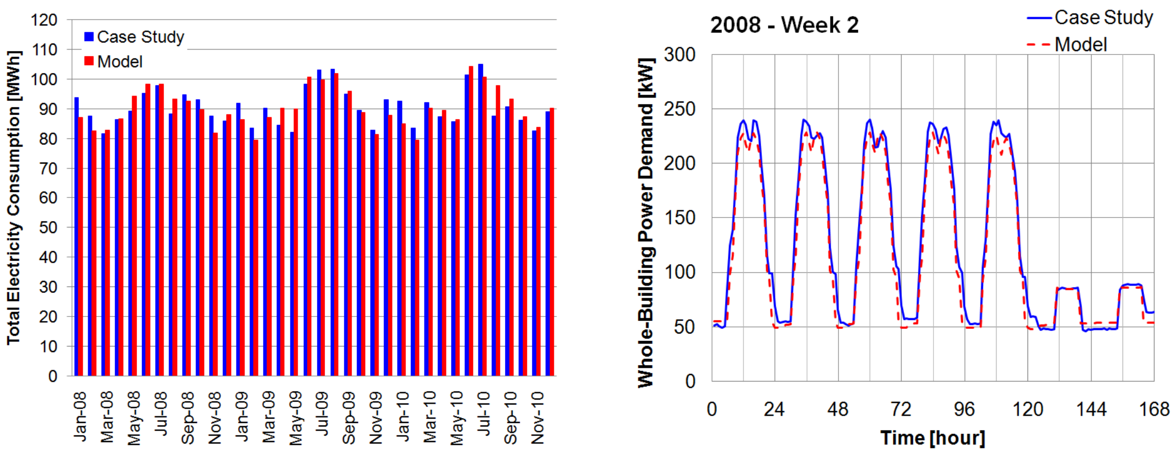

Fig. 6. Predicted (red) vs Recorded (blue) monthly electricity consumptions (left) and whole-building power demand (right).

It is interesting to have a look at the evolution of the major statistical indexes all along the calibration process. The impact of the adjustment of the parameters on the monthly MBE and

CV(RMSE) indexes is very clear during the first stages of the calibration process. After a certain time (level 3: use of monitoring data), the improvement of the quality of the model is not well translated anymore by the mathematical indexes computed on monthly basis (Fig.7 left) and visual verification becomes necessary to check the quality of the model. For step3a (and following), the adjustment of the model is done in order to fit to smaller time-scale data (i.e. monitoring data and whole-building power demand). At this moment, monthly global indexes become unable to catch the improvement of the model. On the contrary, continuous improvements of the model can be noticed when looking at the evolution of the same indexes computed on an hourly basis when comparing computed and recorded whole-building power demand (Fig.7 right).

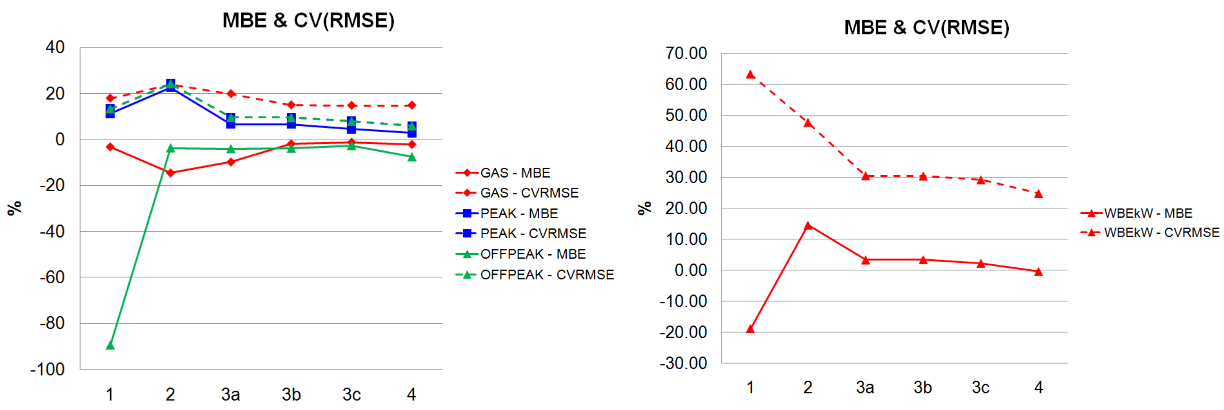

Fig. 7. Calibration levels 1 to 4: Evolution of the statistical indexes for monthly gas and electricity consumptions (left) and hourly whole-building power demand (right)

Calibrated model is then used to disaggregate whole-building electricity consumption (Fig.8). About 33% of the total electricity consumption is due to artificial lighting. Only one third of this part of the consumption is due to lighting in occupancy zones. Offices appliances (computers, printers…) represent about 16% of the total consumption while almost one quarter of the total consumption is due to IT rooms. Ventilation fans are responsible of about 14% of the consumption. The hot and chilled water production and distribution equipment represent about 13% of the total consumption.

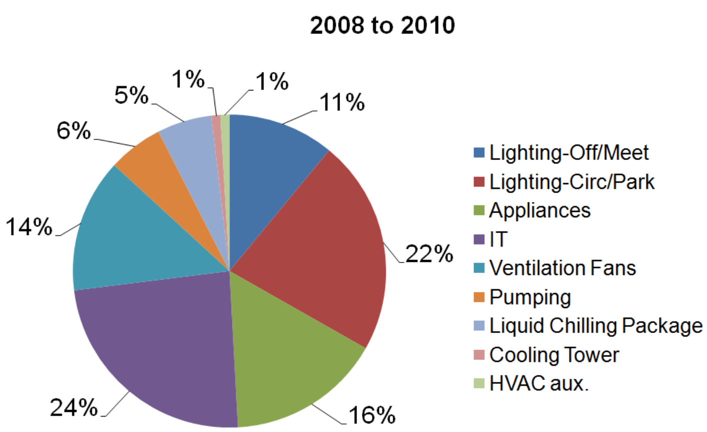

Fig. 8. Whole-building electricity consumption disaggregation

Some electricity users (such as elevators) have not been taken into account in the modeling and cannot be quantified by the simulation model. However, as shown above, the main energy users installed in the building have been taken into account during the modeling phase and the energy use of the neglected ones should not represent more than a few percent of the total energy consumption (i.e. order of magnitude as the final calibration error).

The relative uncertainty (standard deviation) on predicted energy end-use is included between 2.5% and 17%. Lowest uncertainties (between 2.5% and 6%) correspond to internal gains, which have been subject to monitoring (and are characterized by narrowed uncertainty ranges). The energy uses of non-monitored electricity consumers (chillers, cooling towers…) or related to non-monitored energy needs (cooling needs) are characterized by higher uncertainties (between 6% and 17%).

5. Conclusion

The diversity of the buildings composing the non-residential building stock makes hard to derive a general automated calibration methodology that could fit all the cases encountered in practice. It is believed that a flexible evidence-based calibration is needed because:

- Inspection and monitoring needs could vary a lot from case to case, depending on the initial uncertainties on the building/system description;
- Various sources and types of data have to be collected (field observations, BEMS analysis, various types of loggers…) and treated to allow translation into parameters values;
- Statistical indexes that could be used to express an objective function in the frame of an optimization-based calibration approach are too global to reflect all the influences and interactions involved in the model;

This paper presents a new systematic evidence-based calibration methodology giving priority to the physical identification of the model's parameters (i.e. to the direct measurement) and relying on the notion of hierarchy among the source of information (as a function of their reliability) used to identify the parameters. The improved Morris' sensitivity analysis method is used for "factor fixing" (i.e. distinction between non-influential model's parameters) and "parameters screening" (i.e. classification of influential parameters by order of importance) in order to orient the data collection work and guide the parameters adjustment process.

The use of the proposed method and simulation tool ensures sticking to reality and avoids bad representation and hazardous adjustment of the parameters. The intensive use of a sensitivity analysis method is of a great help to orient data collection and parameters adjustment processes. Defining confidence/uncertainty ranges for each parameter, in addition to a "best-guess" value, also allowed quantifying the uncertainty on the final outputs of the model (by means of the LHMC method) and helped the user in evaluating the quality of the calibrated model and criticizing model outputs.

The application of the method to a building case study allowed clearly identifying the potential interactions between the calibration work and the data collection process.The use of a systematic evidence-based method including sensitivity issues allowed optimizing the efforts (i.e. minimizing the monitoring and modeling work while maximizing the quality of the model) and reaching an acceptable level of accuracy. The model was calibrated as the information and data were collected/available: both best-guess values and uncertainty ranges were progressively updated. Finally, the simulation results were analyzed and an uncertainty analysis based on the LHMC method was performed in order to quantify the uncertainty on the final simulation results.

This case study confirmed that it is possible to calibrate a simplified hourly simulation model by means of a relatively little amount of physical measurements if focus is given to critical issues and a systematic and efficient approach is followed. Unfortunately, for practical reasons (loss or unavailability of monitoring equipment), it was not possible to perform, among others, indoor conditions measurements during summer.

In a near future, the next steps of this case study will consist in:

- Perform spot and short-term monitoring during the cooling period to identify the achieved levels of temperature in the zones;
- Setting up online long-term monitoring of the performance of the cooling system (in the frame of the iServ project, Knight 2011);
- Using the calibrated model to make continuous performance verification;
- Evaluating the impact of some modifications of the HVAC system.

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Energy consumption characterization as an input to building management and performance benchmarking – a case study

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Abstract:
The present paper aims at describing the methodology and presents some final results of a work developed in the field of building energy benchmarking applied to the buildings of the Polytechnic Institute of Leiria, based on a thorough energy performance characterization of each of its buildings, looking specifically at the typology of canteen. Developing building energy performance benchmarking systems enables the comparison of actual consumption of individual buildings against others of the same typology and against targets previously defined. The energy performance indicator was computed based on two different relevant elements, the net floor area and number of served meals. Then, the results were ranked according to the percentile rules previously established, and compared. An environmental analysis based on equivalent CO_2 emissions was also performed for each building.

Keywords:
Building energy benchmarking; decision making, energy management, higher education buildings.

1. Introduction

The building sector is very heterogeneous, both in terms of energy consumption and energy end-uses, including highly efficient buildings and others with a high potential for improvement of its energy usage. Overall, buildings are responsible for over 40% of the total final energy consumed in the European Union. In Portugal, residential and service buildings represent about 60% of the electricity consumed, and about 30% of the total primary energy.

Higher education institutions generally own a large stock of buildings which results in a significant overall energy consumption and associated high financial costs. Besides this, it implies overall high emission of CO_2 and its associated consequence on the environment. Good energy management practices results into buildings with better energy performance. One of the ways to achieve this is through monitoring and targeting of energy consumption, which consists in the use of management techniques to control energy consumption and cost (BRESCU 2000).

To implement actions that improve buildings energy efficiency, it is necessary for the building operation to be associated with an effective energy management methodology, as well as an efficient facilities management procedure. The implementation of any energy management system should start with an energy audit (Turner & Doty 2004). An energy audit is a detailed examination of the energy usage conditions in an installation; it is the vital tool that gives the managers the information to support decision making on improving energy performance (Thumann & Younger 2003). Energy audits are not only essential for improving energy efficiency and performance, but also represent a key step in the process of reducing greenhouse gas emissions from buildings, facilities, industrial processes and transport.

The instruments to measure how the energy is consumed, both at the micro and the macroeconomics level, are the energy performance indicators. The energy efficiency indicators can be grouped into two categories according to their objectives: descriptive indicators and explanatory indicators.

The overall performance of a building can be crudely expressed as an energy performance indicator, usually described as a ratio between the total amount of primary energy consumed and a relevant element (e.g. net floor area, number of meals, number of tons produced). The most common indicator in terms of primary energy is energy per net surface (kgoe/m2) and in terms of greenhouse gas emissions is carbon dioxide emissions per energy (kgCO2e/kgoe). The analysis is normally performed on annual data, allowing comparison amongst buildings and with published benchmarks to give an indication of efficiency.

Although performance indicators for buildings are generally rated in terms of net floor area, building volume and the amount of trade (e.g. number of meals) are sometimes used as normalizing factors. Indicators, adjusted according to weather and/or occupancy are often called normalized performance indicators (EVO 2010). This ‘normalization’ is intended to improve comparison between buildings in different climatic regions or with different occupancy patterns. However, this approach should be used with care as it can often distort the data and mask real patterns in consumption (CIBSE 2004).

In recent years, energy benchmarking in buildings has gained prominence with the adoption of the Energy Performance of Buildings Directive (EPBD) in 2002, more specifically the implementation of the Directive through requirements for Operational Rating Certificates and Display Energy Certificates. However, long before EPBD, benchmarks were widely recognized as important for comparing the operational energy efficiency of buildings and for influencing energy policy within building management (Liddiard et al. 2008).

One of the objectives of a benchmarking process is to set targets that will stimulate management to make improvements. These targets must be realistic and achievable, taking into account the likely savings from improvements in people behavior, maintenance and other efficiency measures. Management should use a consultation process to agree individual targets, rather than simply impose arbitrary figures. Targets should be reviewed periodically and set for each cost center, in order to stimulate a positive management attitude (CIBSE 2004).

Energy Benchmarking helps to consistently improve the standards through healthy competition by shifting markets to better performing levels. The potential beneficiaries for Energy Benchmarking include designers, owners, users, building developers, operators and policy makers (Kumar et al. 2010).

2. Methodology

The Polytechnic Institute of Leiria, Portugal, took the initiative of ordering a wide energy performance characterization of its buildings in the several campi. After a thorough energy audit was performed in each building, in order to characterize energy consumption, the buildings were grouped into different typologies, according to the main end-use activity there developed, into pedagogic buildings, canteens, residential buildings, libraries and office buildings. Then, it was required to establish a metric to compare the buildings energy efficiency.

For this study the specific consumption was chosen as the reference energy efficiency indicator. The calculation of the indicators for each building was fed by the data collected in energy audits. Then, the buildings of each typology were ranked and classified into three different categories: Good, Average and Bad. When the measured values present an adequate statistical distribution, the categorization process can be done by quartiles, and so approximately 50% of the sample should categorized as Average, with the respective range limits set to the 25th and 75th percentiles. The specific consumption values in the first quartile (percentile 25th) were categorized as Good and those in the fourth quartile (percentile 75th) were categorized as Bad.

The specific consumption was computed based on two different relevant elements, the net floor area and number of served meals. Then, the results were ranked according to the percentile rules previously established, and compared.

Conversion factors may have a significant influence on building energy consumption and greenhouse gases emission assessment, both in absolute and relative terms, especially when it comes to accounting for electricity. The conversion factors to primary energy used, according to Portuguese norm (Decreto-Lei 80/2006), were the following: 0,290 kgoe/kWh for electricity and 0,086 kgoe/kWh for other types of fuels, parameters defined due to the energy mix of the country. To compute the greenhouse gas emissions, the factors used are the following, according to Portuguese norm (Despacho 17313/2008): 0,47 $kgCO_2/kWh$ for electricity and 2683,7 $kgCO_2/toe$ for natural gas.

3. Data collection and analyzing

Higher education buildings have specific characteristics that differ from other buildings. They usually are grouped together into campi. Since, in most cases, the systems/buildings are not equipped with partial energy meters, the task of determining individual consumption is a true challenge. Besides, these buildings usually have longer opening hours, resulting in longer occupancy when compared with other services buildings. They can also be equipped with laboratories that sometimes resemble industrial facility rather than services building, even if those equipments do not operate continuously.

In the study performed, 25 buildings of the Polytechnic Institute of Leiria were analyzed. These buildings have different locations in the central region of Portugal and were grouped into campi. The main locations are the cities of Leiria, Caldas da Rainha and Peniche. Table 1 summarizes the main characteristics of the buildings analyzed and their typologies.

Table 1: Buildings characteristics.

Building	Typology	Net floor area [m^2]	Energy consumption [kgoe]	GHG emissions [$kgCO_2e$]
C1_Building_A	Pedagogic	4.358	76.111	123.352
C1_Building_B	Pedagogic	1.385	8.797	14.257
C1_Building_C	Office	591	3.953	6.407
C1_Canteen_1	Canteen	842	28.279	56.598
C2_Building_A	Pedagogic	12.063	243.050	434.941
C2_Building_B	Office	3.135	54.221	102.046
C2_Building_C	Research	1.320	37.826	79.782
C2_Building_D	Pedagogic	8.851	274.184	475.605
C2_Building_E	Pedagogic	507	30.378	49.233
C2_Health_School	Pedagogic	4.438	122.670	198.810
C2_Library	Library	3.333	162.246	277.277
C2_Canteen_2	Canteen	2.336	100.281	203.924
C2_Canteen_3	Canteen	1.484	69.146	131.234
C3_Building 2	Pedagogic	2.085	12.422	20.133
C3_Canteen_4	Canteen	1.193	66.133	124.659
Students_Residence_RBP	Residence	1.990	33.755	74.161
Students_Residence_MAD	Residence	1.753	38.867	87.436
Students_Residence_Peniche	Residence	1.019	19.467	43.433
C4_Building_ESTM	Pedagogic	6.542	110.529	184.712
C5_Building_1	Office	2.045	37.280	66.687
Administration_building	Office	2.616	47.813	77.491
Students_Residence_A	Residence	1.460	41.551	86.098
Students_Residence_B	Residence	1.452	38.426	90.419
Students_Residence_ C	Residence	1.744	69.445	133.002
Students_Residence_ D	Residence	1.300	33.173	78.861

Since for the typologies Research and Library there is only one building for each, they will not be subject to analysis.

In Fig. 1 is shown the breakdown of energy consumption by typology of building. For the present paper the focus is the typology of Canteen.

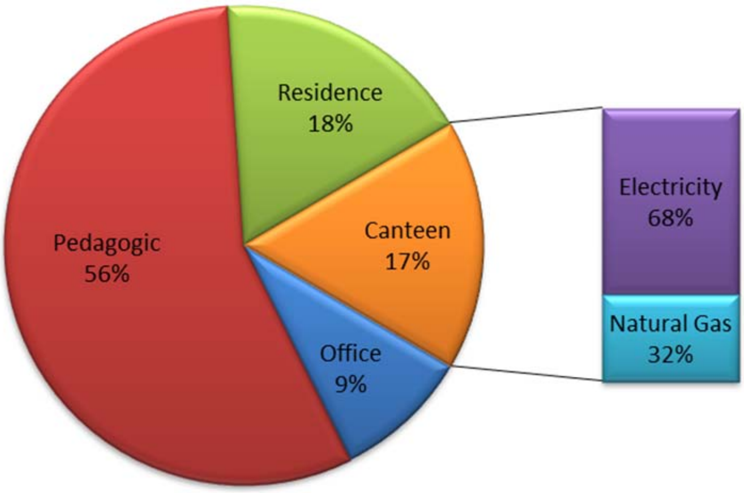

Fig. 1. Breakdown of energy consumption by typology of building.

In Polytechnic Institute of Leiria there are 4 canteen buildings that are responsible for 17% of the total energy consumption. These canteens are fueled by electricity and natural gas and all of them have a centralized system for preparation of domestic hot water fueled by natural gas and supported by a thermal solar system. Table 2 presents the main characteristics of the typology of canteen buildings.

Table 2: Main characteristics of canteen buildings.

Building	Net floor area [m^2]	Number of meals	Energy consumption [kgoe]	GHG emissions [$kgCO_2e$]
C1_Canteen_1	842	89.972	28.279	56.598
C2_Canteen_2	2.336	128.008	100.281	203.924
C2_Canteen_3	1.484	134.711	69.146	131.234
C3_Canteen_4	1.193	57.253	66.133	124.659

On Fig. 2 is shown the fuel breakdown for typology of canteen by each building in terms of electricity and natural gas.

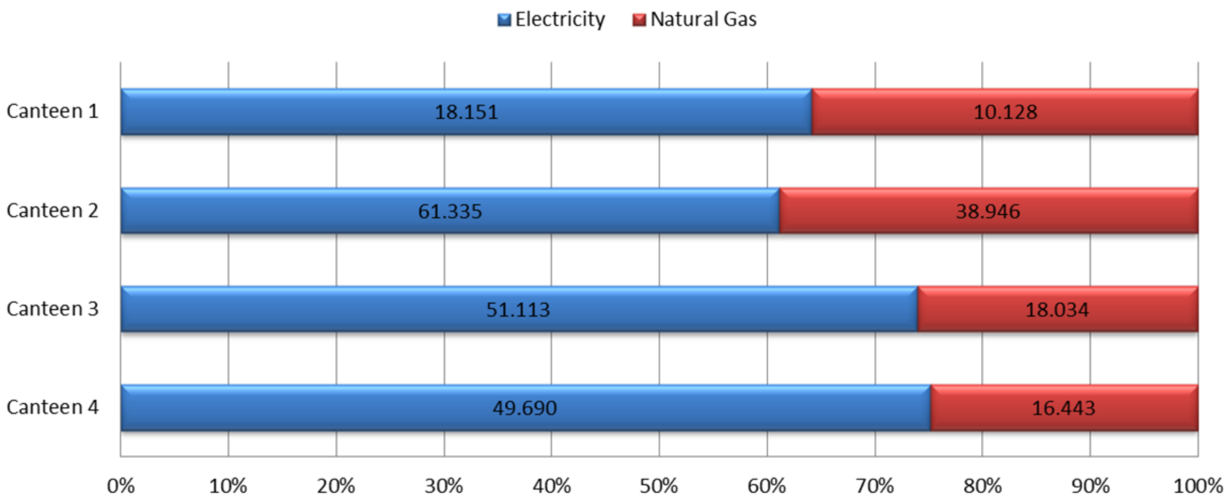

Fig. 2. Fuel breakdown of the typology canteen by each building.

Water and energy usage in canteens are areas that can offer cost savings without compromising hygiene or resources. Managing energy use can often have the additional benefits of improving the quality of the food produced and a better working environment for kitchen staff.

4. Results

The overall results are presented here firstly by showing the relation between energy consumption and net floor area and then the relation between the energy consumption and number of meals. Then, the indicators for both energy and greenhouse gases emissions.

Fig. 3 shows the relation between total primary energy consumption and the net floor area for the typology of canteen. Each mark represents one building.

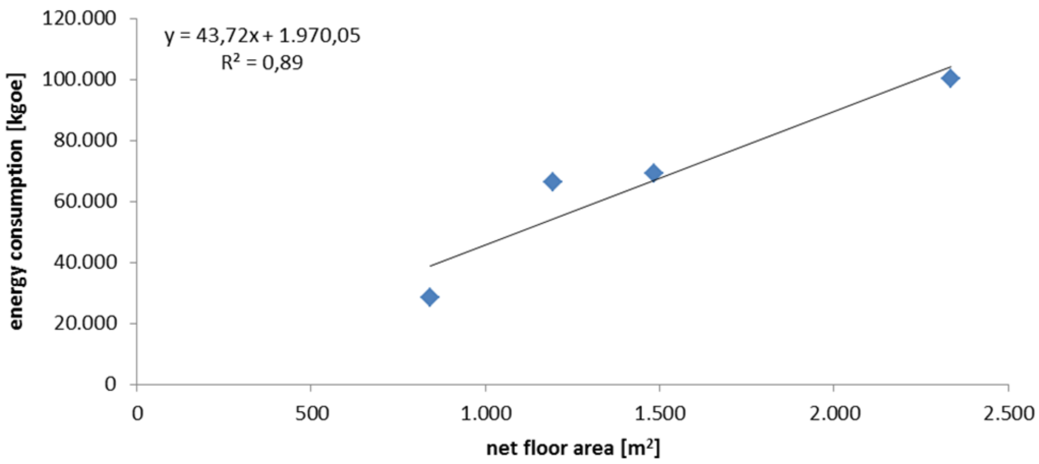

Fig. 3. Variation of primary energy with net floor area.

Fig. 4 shows the relation between total primary energy consumption and the number of served meals in each building for the typology of canteen. Each mark represents one building.

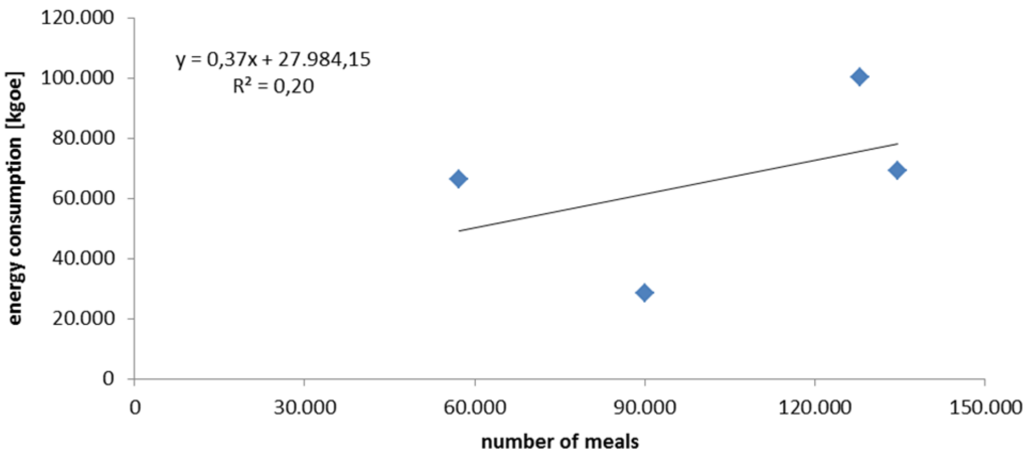

Fig. 4. Variation of primary energy with number of meals.

Analyzing the plots above and looking for linear regression model, it is visible that energy consumption increases with the net floor area of the buildings and with number of meals. However, the plots demonstrate that the relation between energy consumption and the number of meals has widely spread values than the relation between energy consumption and net floor area. The data seems to suggest a reasonable correlation between energy consumption and net floor area, due to the high value of R^2, which suggests that the relation between energy consumption and net floor area is stronger than the relation between energy consumption and the number of meals.

It is normally necessary to reach sample sizes greater than 100 buildings in each building category as this usually provides acceptable frequency distributions and hence reasonably reliable benchmarks. The benchmarks presented should therefore be viewed within this frame of mind and could be regarded as less reliable. However, due to the fact that these buildings are geographically close, and are managed by the same institution, data coherence is enhanced and the results obtained for the main sectors/typologies, where useful data was collected, will be of interest for building managers.

Table 3 presents the performance indicators computed for the typology of canteen. It is patent that different buildings have different specific energy consumptions. For GHG emissions, the differences are not so significant.

Table 3: Computed performance indicators for typology of canteen.

Building	Energy Indicator [kgoe/meal]	Energy Indicator [kgoe/m^2]	GHG Indicator [kgCO_2e/kgoe]
C1_Canteen_1	0,31	33,59	2,00
C2_Canteen_2	0,78	42,93	2,03
C2_Canteen_3	0,51	46,59	1,90
C3_Canteen_4	1,16	55,43	1,88

4.1. Energy indicator

In order to visualize more accurately the range of these differences, Fig. 5 shows 2 boxplots of energy indicator in [kgoe/m^2] and in [kgoe/meal] and Table 4 shows some relevant statistical parameters of energy indicators.

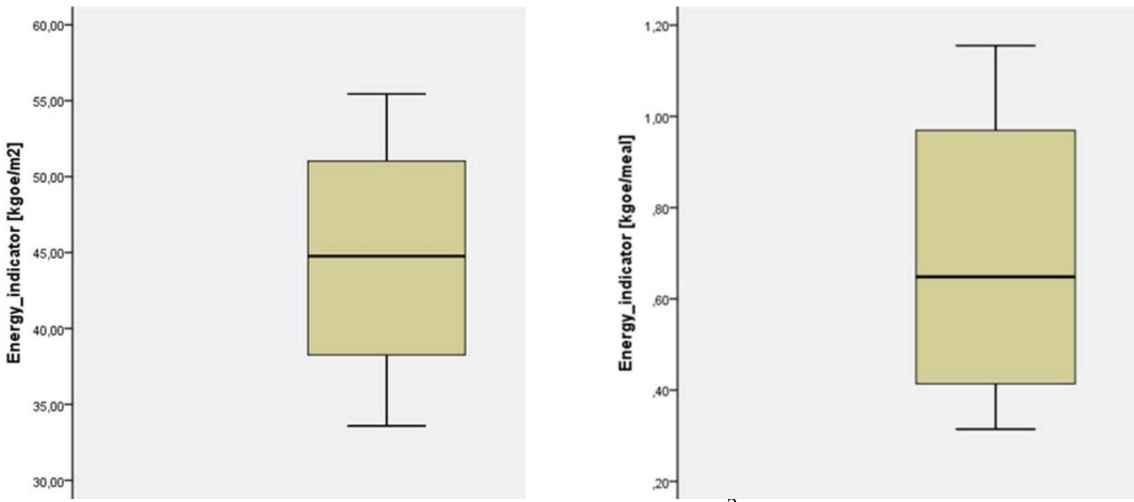

Fig. 5. Boxplot of energy indicator in [kgoe/m^2] and in [kgoe/meal].

The plots demonstrate that when the indicator is computed based on net floor area the data are well distributed along the range, with no outliers and a median near the center of the interval. When the indicator is computed based on the number of meals the interval is asymmetrical and also there are no outliers, which confirms some dispersion of data.

Table 4: Energy indicators for canteen buildings.

Energy Indicator	Sample size	Mean	Standard Deviation	Minimum	Percentile 25th	Median	Percentile 75th	Maximum
[kgoe/ meal]	4	0,69	0,36	0,31	0,41	0,65	0,97	1,16
[kgoe/ m^2]	4	44,64	9,05	33,59	38,26	44,76	51,01	55,43

Applying the quartile-based categorization presented in the second section of the paper, it is thus possible to rank and categorize all buildings using a metric defined accordingly. Fig. 6

presents the buildings, ranked by their energy performance indicator, based on net floor area, and categorized into Good, Average or Bad.

Fig. 6. Buildings ranked by energy indicator [kgoe/m^2].
(Green bars correspond to buildings considered Good, blue bars to Average and red bars to Bad)

Fig. 7 presents the buildings, ranked by their energy performance indicator, based on the number of served meals, and categorized within the rules previously defined.

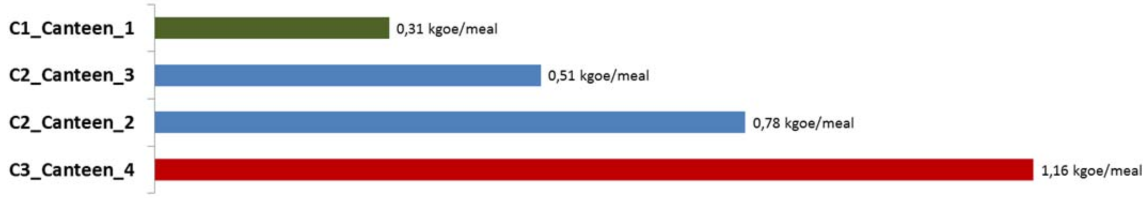

Fig. 7. Buildings ranked by energy indicator [kgoe/meal].
(Green bars correspond to buildings considered Good, blue bars to Average and red bars to Bad)

From this point it is possible to observe each ranking separately, to find curious situations. The best and worst energy performance building remained, but the intermediate changed if the energy performance indicator is calculated based on net floor area or based on the number of served meals. For office buildings, all are similar except for one, and the small size of the sample clearly distorts results. Except for some unapparent exception, the best-ranked building may set an example to the others of its topology, leading building managers to draw the pertinent conclusions.

4.2. GHG emissions indicator

Fig. 8 and Table 5 repeat the previous analysis, for the greenhouse gases emissions indicator for canteens.

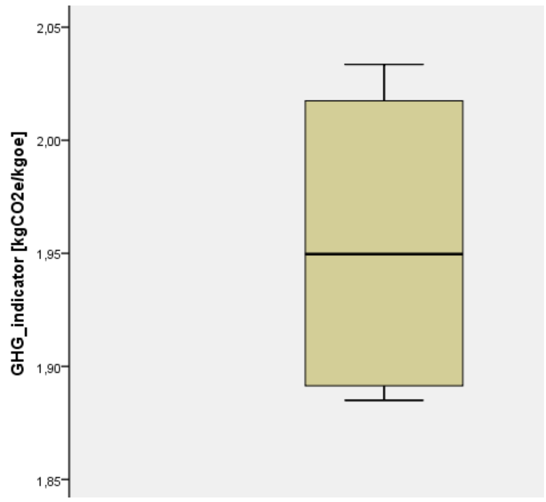

Fig. 8. Boxplot of GHG emissions indicator.

Compared to the previous indicator, this one presents smaller intervals and no outliers, revealing that similar buildings, even with different energy performance, present similar specific GHG emissions. There is some asymmetry in the distribution of the data, since the values are concentrated in the first quartile.

Table 5: GHG emissions indicator for canteen buildings.

GHG Indicator	Sample size	Mean	Standard Deviation	Minimum	Percentile 25^{th}	Median	Percentile 75^{th}	Maximum
[$kgCO_2e/kgoe$]	4	1,95	0,07	1,88	1,89	1,95	2,02	2,03

Applying the quartile-based categorization presented previously, it is thus possible to rank and categorize all buildings using a metric defined accordingly. Fig. 9 presents the buildings, ranked by their GHG emissions indicator, and categorized into Good, Average or Bad.

Fig. 9. Buildings ranked by GHG emissions [kgCO2e/kgoe].
(Green bars correspond to buildings considered Good, blue bars to Average and red bars to Bad.)

According to the previously results it can be seen that the building that have the worst energy performance indicator is the best in terms of environment and GHG emissions and the building with better energy performance indicator belongs to the worst ones in terms of GHG emissions. In terms of environmental performance the better buildings are those which have less natural gas consumption.

5. Conclusions

Performance indicators give only a broad indication of building efficiency and therefore must be treated with caution. It should not be assumed that a building with a ‘good’ performance indicator is in fact being operated as efficiently as is possible, or offers no scope for cost-effective savings. Overall performance indicators can mask underlying problems with individual end uses of energy.

The study performed is useful to identify if the buildings energy performance is poor, average or good comparing to the same type of buildings and to provide a useful first indicator for support decisions on the implementation of actions that improve buildings energy efficiency. When considered as a whole, the results allow further knowledge on the overall energy consumptions of a set of buildings, which in term may aid the decision-making process, for instance when evaluating different investment options, or when ordering a list of priority of interventions according to each actual effectiveness and pertinence.

At the beginning of the study it was expected that the energy consumption has stronger dependency with the number of served meals than with net floor area, but that was not true for Polytechnic Institute of Leiria. This may be due to the small number of buildings available to study or perhaps suggest that the matter requires further studying to be performed in order to assess the best indicator to use. Nevertheless, similar studies should be performed with a larger number of buildings, from different typologies, in different sectors of the economy. For example, it would be very interesting to perform a study of this nature throughout the higher education sector of Portugal.

Energy efficiency in buildings operation only can be achieved through a continuous energy monitoring and management system. So, energy benchmarking is also useful to give the measure of the progress over time.

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Moving Towards Net-Zero Energy of Existing Building in Hot Climate

Abstract

This paper presents the results of an extensive program of energy conservation and energy generation using integrated photovoltaic (PV) modules. The program conducted on an existing institutional building intending to convert it into a Net-Zero Energy Building (NZEB) or near net Zero Energy Building (nNZEB). The program consists of three phases; the first phase is concerned with energy auditing and energy conservation measures at minimum cost and the second phase implements a Building Management System (BMS) whereas the third phase considers the installation of photovoltaic modules in the building roof to provide considerable portion of the energy consumption in the building.

The first phase results in an energy conservation of 6.5% of the building consumption. The second phase yields further reduction of the building energy consumption by about 55.4%. The average payback period of most energy conservation measures is about half year. In the third phase, approximately 27% of the total energy consumption with a payback period of less than 9 years and a saving of about 160 tone/year of CO_2 emission can be accomplished.

Keywords:

Building integrated photovoltaic systems, energy conservation, green house gases, Net-Zero Energy Building, payback period.

1. Introduction

Net-Zero Energy Buildings (NZEBs) are those buildings which, on an annual basis, produce energy from renewable sources that equals the amount of consumed energy by the building. If the produced energy from the building is slightly less than consumed; such building is called nearly net zero energy building (nNZEB). The NZEBs comply with the concept of sustainability that requires balanced conditions among energy, economy, and environmental aspects. The NZEBs concept is increasingly recognized worldwide. For instance, European countries has issued a legislation starting from July 2012, that public buildings have to be nearly zero energy building by the end of year 2018, while all other new buildings should follow the same trend by the end of 2020. On the same aspect, ASHRAE assign a target of net zero energy buildings fulfillment by 2031. Generally, these types of buildings design efficiently in the first place, so thus renewable energy can provide a satisfactory portion of the building consumption with feasible economic analysis.

In order to achieve NZEB or nNZEB, existed and newly designed buildings must be energy efficient before any integration of renewable energy is to be considered. This task is not a straightforward; therefore many guidance standards have been published to lead designer on such track. Fortunately, large interest by public on building rating system such as Leadership in Energy and Environmental Design (LEED), Building Research Establishment Environment Assessment Method (BREEAM), and Qatar Sustainability Assessment System (QSAS) which audits the building process from design to construction to ensure the compliance of building to a certain standard of performance.

The newly designed buildings may face challenges to fulfil the requirements of NZEBs, but these challenges become even more difficult for existing buildings. Thus, the existing buildings should undergo an energy auditing and energy conservation processes before considering any power generation process. Although existing buildings receive less attention by the authorities, designers, clients, and even the building rating system organizations, ASHRAE-100 (2006) introduces energy audit standard for existing building that may be followed. Many research works have implemented such or similar audit standard and the results showed substantial energy reductions (Li, 2008; Iqbal, and Al-Homoud, 2007; Escrivá-Escrivá, et al., 2010; Mills, et al., 2004; Rahman, 2010).

Recently many new and existing buildings incorporate solar energy technologies to attain environmental benefits in comparison to the conventional energy in terms of reducing global warming and greenhouse gases emissions, mainly CO_2, and preventing toxic gas emissions. The most common type is photovoltaic (PV) modules which can be installed on buildings' roof to avoid the cost of land use, and the support structures for the modules. Building-integrated photovoltaic systems (BIPV) is considered as one of the most cost effective application of PV systems in terms of energy payback time and avoided CO_2 emissions and it is expected that they can reach widespread commercialization in the near future (16).

Aristizábal et al., (2008) studied the operation performance results of the first grid-connected building integrated photovoltaic (BIPV) system installed in Colombia. Their results indicated that the power generated by the grid-connected BIPV plant fulfils the specifications demanded for such systems by National and International standards. The potential impact in energy demand reduction at the Florianopolis International Airport in Brazil with the use of building-integrated photovoltaic (BIPV) systems is analyzed by Rüther et al., (2009). Their results showed that the integration of PV systems on airport buildings in warm climates can supply the entire electrical power consumption of an airport complex, in line with the general concept of a zero-energy building. Yoon et al., (2011) carried out an analysis of building integrated photovoltaic (BIPV) modules on the windows covering the front side of a building by using transparent thin-film amorphous silicon solar cells. The analysis is performed through long-term monitoring of performance for 2 years. They concluded that the measured energy generation efficiency in the tested condition can be improved up to 47% by changing the building location in terms of azimuth and shading, thus allowing better solar radiation for the PV modules.

A life cycle inventory model is presented by Keoleian et al., (2003) to characterize the energy and environmental performance of BIPV systems relative to the conventional grid and displaced building materials. They concluded that the displacement of utility generated electricity and conventional building materials can conserve fossil fuels and have environmental benefits. The model is applied to an amorphous silicon PV roofing in different regions across the US. The electricity production efficiency (electricity output/total primary energy input excluding insulation) for a reference BIPV system ranged from 3.6 to 5.9 indicating a significant return on energy investment. Castro et al., (2003) evaluated the limits and competitiveness of PV energy in Spain considering technological, economic, social and environmental aspects. The authors concluded that for the year 2020, the total grid-connected BIPV installed surface could reach 2,480,000 m^2, supplying as much as 1,872 TJ per year, 10% of the electricity peak demand in the summertime and providing up to 25,000 jobs.

In the present work, a mid-size existing institutional building is considered as a model for existing public buildings that moving toward NZEB in Kuwait. This study has two purposes; the first is to carry out an energy audit to reduce the energy consumption in the building to its lowest possible value by implementing the appropriate energy conservation measures. The second objective is to design building integrated photovoltaic system (BIPV) in Kuwait to achieve Net Zero/near Net Zero Energy Building (NZEB or nNZEB). In addition, the performance and environmental impact of the designed building integrated photovoltaic system (BIPV) is evaluated.

2. Building Status and Energy Consumption

The first step in conducting an energy auditing is to define the current situation of the building in order to propose the appropriate energy conservation measures. The building under consideration is the Mechanical Engineering Department in the College of Technological Studies, Kuwait. It is a 2-storey building with a total floor area of 7020 square meters. The long side of the building is oriented toward the east-west direction with 4 main entrance doors on east side. On average, 350 people use the building with irregular occupancy from 8 am to 5 pm, 5 days per week during the academic sessions. The building wall construction can be considered heavy mass, with an overall heat transfer coefficient of 0.562 W/m^2K, a common practice in very hot climates (such as those in the State of Kuwait). The wall consists of 3 cm of cement then two 10-cm thick hollow core cement block layers with a 5-cm rigid fiber glass insulation layer embedded in between; inner 2-cm thick plaster. Most of the roof of this building was constructed from light mass construction that is well insulated with an overall heat transfer coefficient of 0.187 W/m^2K. It consists of 4 layers: a layer of roof sheeting, 15 cm of insulation, a layer of air space, and a layer of ceiling tile; the mentioned layers are arranged from the outermost to the innermost layer. The windows and entrance doors are aluminium-framed constructed from 6 mm double-tinted glazing with an overall heat transfer coefficient of 3.42 W/m^2K.

The heating, ventilation and air-conditioning (HVAC) system of the building consists of 4 air-cooled reciprocating (semi-Hermetic) chillers using R407c refrigerant. Three of the chillers are typically on duty while one is on standby, and each has a capacity of 223.52 kW. The integrated distribution system consists of 14 air-handling units (AHUs) of constant air volume (CAV) that serves the staff offices, classrooms, and laboratories. The only part of the building that is designed to utilize a variable air volume (VAV) is the administrative section. The remaining part of the building consists of workshops, and they are serviced by 30 fan-coil units (FCUs).

In a harsh hot weather such as the case in the State of Kuwait, it is expected to find that the HVAC system is the most energy consuming equipment in buildings. In this study, the HVAC system and its distribution system consumes 87% of the total building energy consumption. This total value of HVAC system energy consumption is split between the chillers system, 41%, and its air and water distribution systems (such as air handling units, variable air volume boxes, fan coil units, and pumps), 46%. The remaining energy consumption is distributed between lighting system, 9%, and equipment, 4%.

3. Phase-I: Energy Conservation at Minimum Cost

To assess the energy consumption of the building, an energy index which is also known as energy utilization index (EUI) is calculated by dividing the annual energy consumption by the gross floor area. This index is used to compare the energy consumption among buildings of a similar nature. In the same region, the measurements conducted for a fairly new construction office building show an annual EUI of 315 to 410 kWh/m^2 (Alajmi, 2012). Figure 1 presents a comparison between the studied building and the typical building using this type of index. The comparison shows an opportunity of energy saving in the building by about 50%.

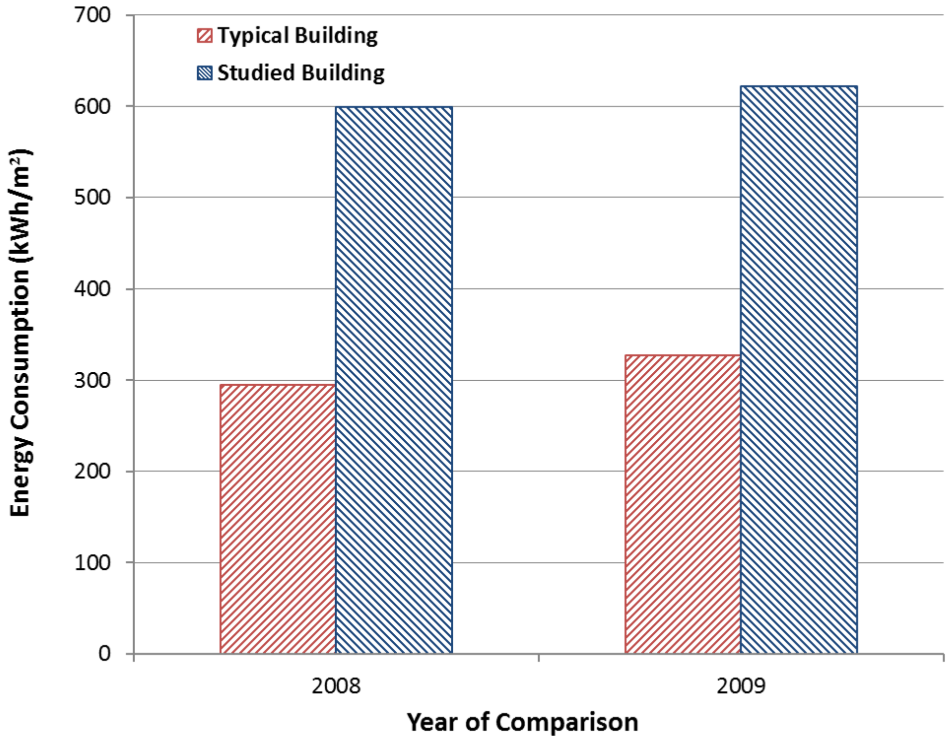

Figure 1: Energy consumptions comparison of studied and similar building.

An energy audit team has carried out a preliminary assessment, which revealed an inefficient practice upon the building and by the occupants. The building roof was partially damaged which left the steel structure of the roof bare of insulation, increasing thermal loading on the building. In addition, the main entrance and emergency doors were deliberately left open for a long time while the HVAC system was running. This increases the amount of air infiltrated into the building and consequently the HVAC energy consumption dramatically.
Moreover, visits at night and weekend to the building revealed that the lights and plug-in equipment of some offices were left on after working hours (Fig. 2) and during the weekends (Fig. 3). In addition, the light intensity has been measured in offices, laboratories, workshops, classrooms, and corridors was found to be 730, 1084, 926, 934, and 556 lux, respectively, whereas the recommended intensity levels are 500, 500, 750, 250, and 150 lux, respectively. All luminaries used in the building are the T-8 type. Therefore, it was recommended that some lamps in the overly illuminated areas be removed or disabled and T-5 type lighting is suggested as an efficient replacement.

In general, to reduce energy consumption, it is important to increase the awareness of the users to switch off the room lights and equipment before leaving. This could also be checked by the security officer. Table 1 lists the potential opportunity of energy conservation that could be achieved by applying the above mentioned energy conservation measures. An annual saving of 290 MWh can be achieved as a result of applying the preliminary auditing of the building.

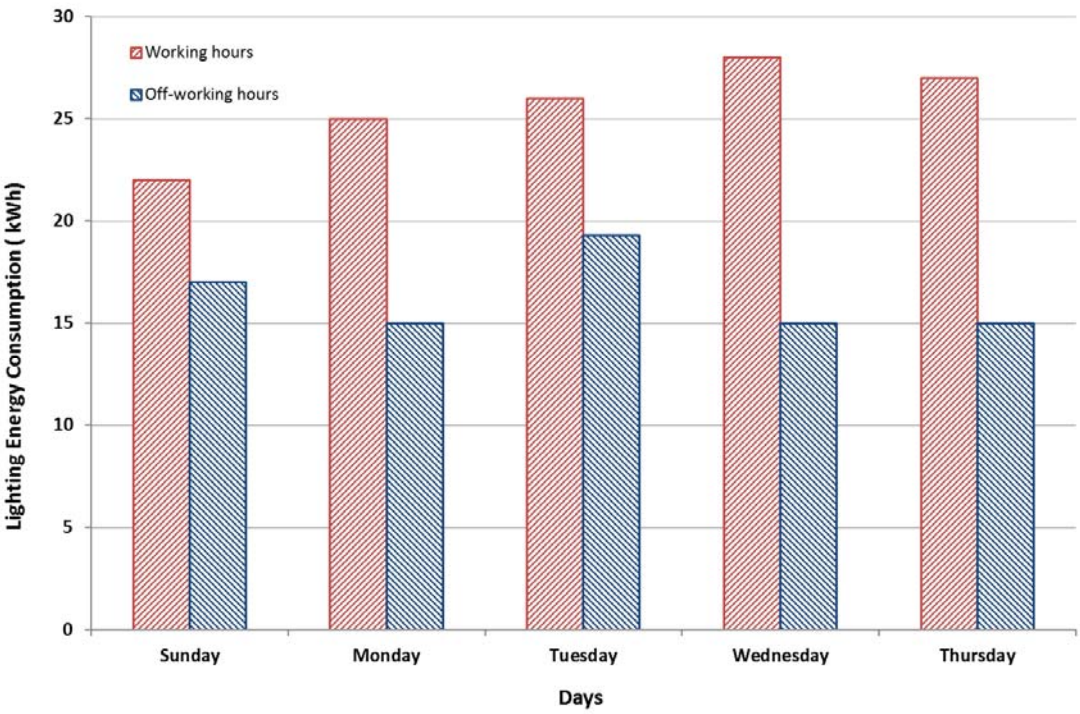

Figure 2: Energy consumption of lighting during working and off-working hours.

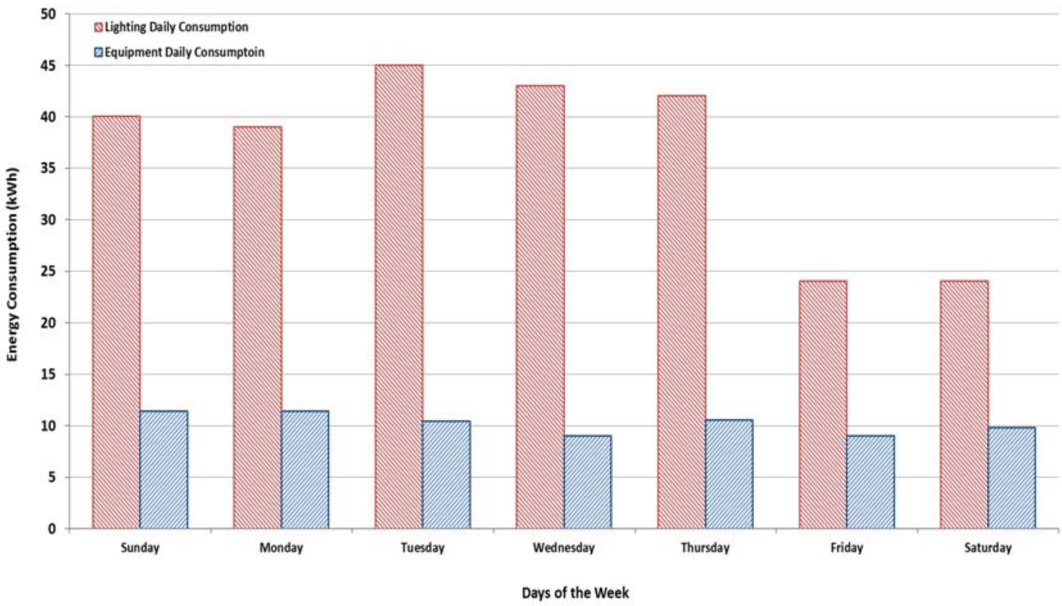

Figure 3: Energy consumption in the building during week days and week end.

Table 1: Energy conservation with minimum cost

(% energy savings are based on the average building consumption of 4.44 GWh).

No.	*Recommended Actions*	*Energy saving GWh/year*	*% energy saving*
1	*Schedule lighting operation*	*0.10*	*2.3*
2	*Schedule office equipment*	*0.01*	*0.2*
3	*Reduce infiltration*	*0.18*	*4. 1*
	Total	***0.29***	***6.5***

4. Phase-II: Energy Conservation with Investment (Building Management System)

4.1 Monitoring and Analysis of the Building Performance

The possible opportunity of energy saving indicated in Fig. 1 is not satisfied with the slight achievement of the preliminary study conducted in phase I. Thus, the energy audit team decided to conduct a detailed study to provide sufficient information for thermal performance evaluation of the building. For this reason, microcomputer data-loggers that have built-in sensors for dry-bulb temperature, relative humidity and light intensity, are installed in each zone of the building to monitor the building's characteristics from April to October. The collected data showed that usually the indoor air temperature was 1-5°C below the thermal comfort temperature (24°C for summer) in the ground and first floors of the building. This explains the continuous complains of over-cooling by the building users. This building overcooling unnecessarily consumes excess energy by the HVAC system.

4.2 Upgrade the HVAC System Control

In the detailed energy auditing, the team-work found that the HVAC system is operated manually and all the 3-way valves of the AHUs were not functioning properly, i.e., they were not responding accurately to the air supply or to the return air temperature. Also, the 3-way valves of the FCUs were not functioning properly as they may be leaking. This is revealed by indoor temperatures of the workshops (most uncomfortable areas as stated by the users) that is usually lower than the set points causing continuous overcooling. Based on the above observations, it became evident that the indoor environment was not accurately controlled and the number of working chillers was directly linked to the occupant complaints and the operators' judgment.

It is clear from the above discussion that the manual operation of the chillers does not provide accurate control of the building environment. Thus, incorporation of direct digital control (DDC) closely controls the building environment, enhances building operation and saves considerable amount of energy. After verification of the simulated energy consumption of the building against the actual building load, 46.2% of the annual building energy consumption can be saved by the proposed actions as listed in Table 2. An energy saving of 23.4% can be achieved if the indoor air temperature is maintained at 24 ºC (comfortable dry-bulb temperature) during working hours. An additional energy saving of 5.6% can be achieved if the temperature is set to 28 ºC after working hours. Additional, 13.3% and 1.3% of the building's energy consumption can be saved if the HVAC system is switched off during weekends and proper operation and maintenance are exercised, respectively. As the lighting is considered the second largest item that consumes energy in the building, more efficient lighting or better operation yields a saving of 2.3% of the total energy consumption. Ultimately, by increasing the roof insulation, a saving of 0.3 % can be obtained.

Table 2: Energy conservation with investment.
(% energy savings are based on the average building consumption of 4.44 GWh).

No.	***Recommendations***	***Energy saving GWh/ year***	***% energy saving***
1	*Control Indoor Temperature to 24 ºC*	*1.040*	*23.4*
2	*Set-back Temperature to 28 ºC*	*0.250*	*5.6*
3	*Turn off HVAC during weekends*	*0.590*	*13. 3*
4	*Proper maintenance and operation*	*0.056*	*1. 3*
5	*Efficient lighting (T5)*	*0.100*	*2. 3*
6	*Increase roof insulation*	*0.014*	*0.3*
	Total	***2.050***	***46.2***

4.3 Chillers Operation Strategies

Designers and practitioners used to oversize the HVAC system by certain value which is sometimes overestimated. This makes the HVAC system running at partial load most of the time. In such circumstances, the search for the appropriate operation strategies for different building use and conditions is essential in order to achieve acceptable energy consumption of the oversized chilled water plant. These strategies may be used to program the controlled-operated chillers or even used directly for those chillers operated manually. These appropriate operation strategies can lead to considerable energy saving of the existed chillers particularly for oversized systems. Many operation scenarios of the chillers were tested and found that the best scenario saves about 20% of the energy consumed by the worst scenario. In addition, the best scenario involves the use of only two chillers instead of three which results in longer life time of the chillers system as half the available chillers are used alternatively.

The chillers operate at low performance when working at partial load outside the working hours. The coefficient of performance of the chillers during off-working hours dropped to 1/6 of the value during the working hours. For this reason, it is recommended to use the chillers when working efficiently and to avoid using them when working inefficiently as this will considerably contribute to energy saving. Therfore, a new shcedule is proposed to switch off the chillers at the start of the non-occupied period and to start them again in the early morning to cover the heat stored in the building at night. Thus, the stored heat will be removed at the start of the working day when the chillers are running at full load and have up to six times better performance, i.e. the stored heat will be removed with less amount of energy. This operation strategy saved about 13.2% of the chiller consumption during any period of application.

Efficient operation of the HVAC system during the summer vacation is also considered. The actual reduction, in the building load during summer vacation, is caused by switching off the building's lighting and equipment, by setting-back indoor temperature to 28°C and finally omitting the people load, infiltration and ventilation,. Therefore, a plan for the operation during summer vacation is to reduce the chillers consumption by half during the day and switch them off at night. This plan should save up to 50% of energy consumption during summer vacation, i.e. 53700 kWh a year that represents about 2.8% of the total energy consumed by the chillers.

Accordingly, as the required chillers capacity is half the available capacity, the water flow rate can be reduced by half without affecting the HVAC system performance. In order to achieve this, a modification of the existing water distribution system is proposed. In the new arrangement of the water distribution system, the water flow diagram is split into 2 circuits where two pumps and two chillers are existed in each circuit. Therefore, only two pumps will be working alternatively. The reduction of the number of running pumps from four to two would save 50% of the annual pump consumption (19.8 MWh) which represents about 3% of the annual HVAC energy consumption.

Table 3 summaries the expected energy saving of the chillers consumption by implementing the above discussed operation strategies and measures. Total energy saving of about 21.5% (408 MWh) of the annual chillers consumption could be achieved which represent 9.2% of the building consumption.

Table 3: Summary of chiller energy saving for different proposed strategies
(% energy savings are based on the chiller consumption of 1900 MWh).

Chillers Operation	***Energy Saving MWh/year***	***% Energy Saving***
Select the best operation scenario	*84.5*	*4.5*
Switch off chillers during non-occupied period (overnight)	*250.1*	*13.2*
Reduce chillers capacity by half during vacation	*53.7*	*2.8*
Reduce pumps capacity by half	*19.8*	*1.0*
Total (% energy savings with respect to chiller consumption)	***408.1***	***21.5***
Total (% energy savings with respect to building consumption)	***408.1***	***9.2***

5. Cost Analysis and Payback Period for the Different Measures of Energy Saving

Implementation of the first and second phases yields considerable energy savings as it reduces the annual energy consumption of the building from about 4.44 GWh to 1.15 GWh in 2012. Figure 4 shows the effect of implementing the energy conservation measures over these years. To evaluate the feasibility of implementing different approaches to reduce existing building energy consumption, the auditor has to calculate the payback period. Most calculations can be performed using the simple payback approach by dividing the capital cost of the measure by the cost of the anticipated annual energy savings to obtain the payback period in years. The amount of money saved annually is calculated by multiplying the national tariff, which is equal to 0.012 USD/kWh, by the anticipated energy savings.

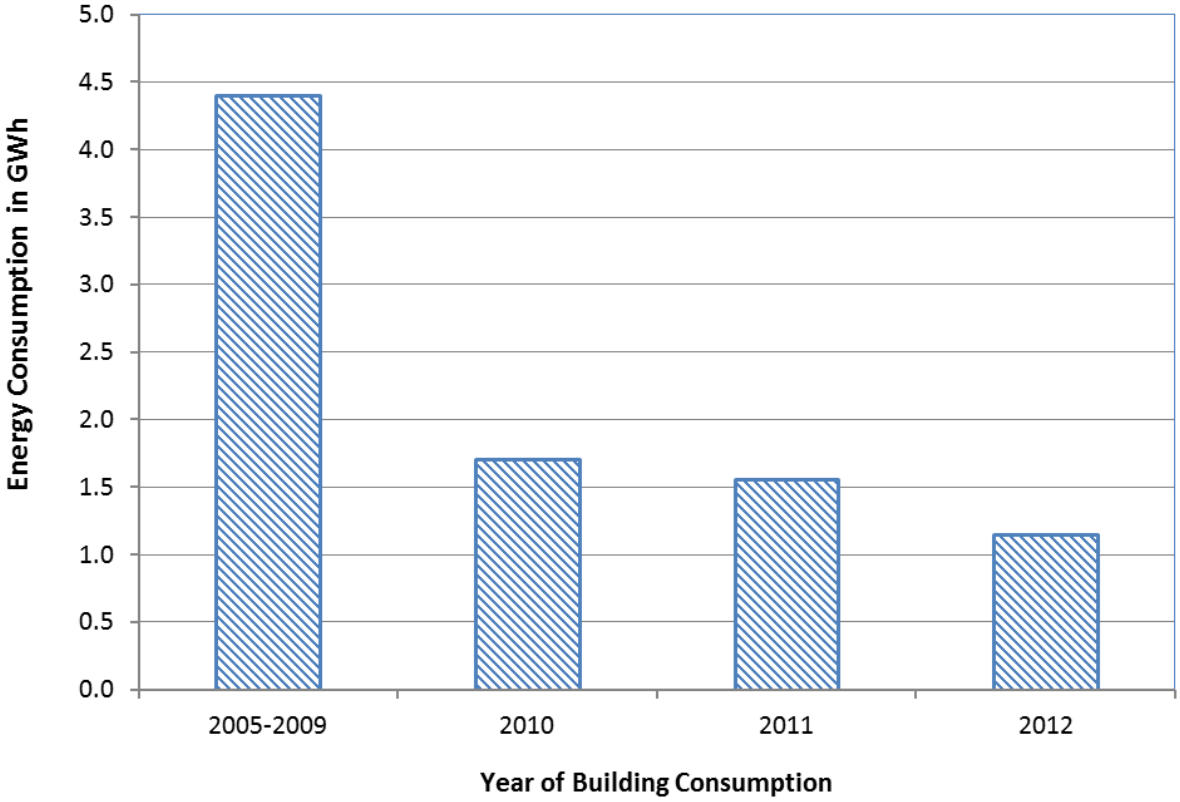

Figure 4: Effect of energy conservation measures on the building consumption

The implementation of the first phase recommendations does not require retrofitting and requires the cost of energy audit team only whereas the second phase measures require retrofitting at an additional cost. Table 4 presents the total list of recommendations along with their savings analysis. For phase II, the first 3 items can be implemented simultaneously by installing a building management system (BMS), while the other remaining items can be implemented individually. Encouragingly, the table showed that the cost of installing a BMS that addresses the first 3 items can be paid back in less than half a year. The core function of the BMS is to manage the environment within the building by controlling the temperature and humidity. Therefore, it controls heating and cooling and manages the systems that distribute air throughout the building. It was found that the existing HVAC system can be easily integrated with a BMS.

The payback period of changing to more efficient lighting was reasonable; however, this may cause significant interruptions to the users of the building. The payback period of increasing roof insulation by 2.5 cm was relatively acceptable. Finally, the payback period of properly maintaining and operating the HVAC system was less than 17 months.

Table 4: Cost Analysis and Payback Period for Energy Conservation.

		Savings Analysis		
		Annual cost savings (USD/yr)[1]	*Cost of energy audit team or retrofit (USD)*	*Simple payback period (yr)*
energy reduction in phase-I	*Lighting schedule*	*13,408*		
	Equipment schedule	*1,190*	*18311*	*0.5*
	Reduce infiltration (close doors)	*23,490*		
energy reduction in phase-II	*Control indoor temperature*	*136,886*		
	Temperature setback to 28 °C	*33,660*	*109,869*	*0.5*
	Turn off HVAC during weekends	*78,509*		
	Select the best operation scenario			
	Switch off chillers during non-occupied period (overnight)	4,896	5,250	1.1
	Reduce chillers capacity by half during vacation			
	Reduce pumps capacity by half			
	Efficient lightings (T5)	*13,558*	*16,261*	*1.2*
	Increase roof insulation by 2.5 cm	*1,680*	*7,325*	*4.4*
	HVAC maintenance	*7,336*	*10,071*	*1.4*

[1] Exchange rate of U.S. dollars (USD) to Kuwaiti dinar (KWD) 1 USD = 0.273 KWD

6. Phase-III: Building Integrated Photovoltaic (BIPV)

The third phase is concerned with integrating the building with photovoltaic modules to provide the energy consumption of the building in an attempt to convert it into NZEB or if the generated amount of energy is less than the energy consumption, the building will be nNZEB. As this phase is crucial for moving towards NZEB, more insight analysis is presented for the parameters controlling the BIPV.

The weather data used in this study have been measured and collected for over two years in the College of Technological Studies, Kuwait. The weather data used are hourly values of daily radiation on horizontal surface and ambient temperature.

6.1 Hybrid Photovoltaic System Components

Stand-alone PV systems are designed to operate independent of the electric utility grid, and are generally designed and sized to supply DC and/or AC electrical currents. A hybrid photovoltaic system is proposed for the present work as shown in Fig. 5. This may be an economical alternative to a large standalone PV system, because the PV array does not have to be sized large enough for worst weather conditions. The PV array charges the battery during daylight hours and the battery supplies power to the loads as needed. The battery charging process is terminated by the charger regulator when the battery is full. The electricity is started during extended overcast situations or at periods of increased load. When the batteries are low, the electricity will power the AC loads in the building as well as the battery charger.

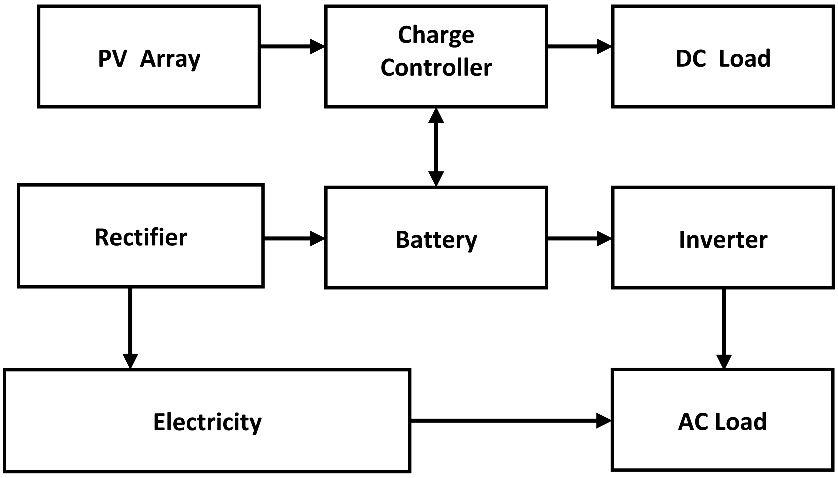

Figure 5: Diagram of building integrated hybrid photovoltaic system

The system includes a DC to AC inverter to convert the direct current (DC) produced by the PV array to alternating current (AC) which is required by most household appliances. Disconnect switches are needed for system servicing and personnel safety. They are typically installed on the inverter's input and output, at the array output, and on the battery bank's output. Most disconnect switches also include over-current protection, either as fuses or circuit breakers. The system usually requires a maximum power point tracker that monitors PV outputs such that the PV always operates near its point of maximum power along the IV curve.

6.2 PV Model

In the present work, the five parameter model (Ghoneim, et al., 2002) is used to simulate the characteristic of polycrystalline solar cells at different weather conditions. This model adds the shunt resistance to the four-parameter model. Adding this parameter makes this model applicable to both crystalline and amorphous PV solar cells. At a fixed temperature and solar radiation, the current-voltage characteristic for the five parameter model is given by:

$$I = I_L - I_D - I_{sh} = I_L - I_o[\exp(\frac{V + IR_s}{a}) - 1] - \frac{V + IR_s}{R_{sh}}$$

Where, I current at the load, I_D diode current, I_{sh} shunt resistance current, I_L photocurrent, I_o diode reverse saturation current, V voltage at the load, R_s series resistance, and R_{sh}, shunt resistance.

The solar radiation processor subroutine (TYPE 16) included in TRNSYS (Klein, et al., 2006) calculates the incidence angle for the beam component of the radiation. Duffie and Beckman (2004) have suggested additional correlations to determine the effective incidence angle for diffuse and ground reflected radiation.
Each simulation has a length of one year period and employing polycrystalline solar cell (Siemens SR100) rated at 100 Wp. The subroutine of the five parameter model is implemented into TRNSYS to determine the output of the PV system using the incident radiation on the array surface and the ambient temperature.

6.3 Performance Characteristics of the PV system

The data presented in this section are for polycrystalline silicon modules. This technology was chosen as polycrystalline silicon technologies are the most widely used for PV systems. Assumptions of angle of orientation, local temperature and radiation levels, inverter efficiency and module efficiency are the most important factors that determine the output of the PV system. Each simulation has a length of one year period and employing 1400 polycrystalline solar modules rated at 100 Wp. Characteristic data of these modules are obtained from manufacturer's catalogue (Siemens; 2011). The SR100 modules are a large single crystal module representing the most widely used PV technology. Each module has an area of 0.89 m^2, so the entire PV array area is about 1246 m^2. The roof area of the building adapted is about 1440 m^2 which is large enough that the rows may be spaced widely to minimize shading losses. The inverter is considered to have a constant efficiency of 92% in the present calculations. The subroutine of the five parameter model is implemented into TRNSYS to determine the PV output. Each simulation evaluates the energy generated from a 140 kWp array placed on the building roof. The data used are weather data, building load, utility rate schedules and total utility demand.
The weather data used are hourly global solar radiation on horizontal surface, and hourly ambient temperature. It is worth to mention that the total building load in each month is also calculated. Usually, the output of PV array is optimum if the PV array is facing south and has an orientation equal to the latitude. However, this conclusion is not general since the optimum orientation should depend on the location and weather conditions.
Figure 6 presents the variation of the annual energy production for various PV orientations. The slope of the PV array is changed from 0° to 60° (i.e. latitude ± 30°). In addition, different azimuth angles are examined ranging from 0° (due south) to 40° west of south. Each combination of slope and azimuth angle is examined in a single simulation period which is one year. As seen from the figure, the energy production changes with both array orientation and azimuth angle. It is obvious that the maximum energy generation from the PV arrays corresponds to array slope equal to 40° (i.e. latitude+10°) and for arrays facing south (azimuth angle=0°). The annual PV generation in this case is about 273 MWh. The energy output decreases by about 2.6 MWh (less than 1%) from a surface azimuth of 0° to a surface azimuth of 40°. Maximum energy production at angles greater than latitude is in accordance with the fact that more solar energy is available in summer than in winter in Kuwait. So, annual energy production can be maximized by using an array sloped at an angle 10° greater than the latitude. This orientation will reduce the average angle of solar incidence during the

summer when the sun is high in the sky and more radiation is available. It is also found that the energy production from 140 kWp PV array satisfies a reasonable fraction of the total load of the studied building (about 27%). It should be noted that the maximum PV capacity which can be adapted for the building under study is 140 kWp according to available roof space. However, if a flat rate per unit kWh is assumed, the optimal array orientation for energy production should also maximize solar savings.

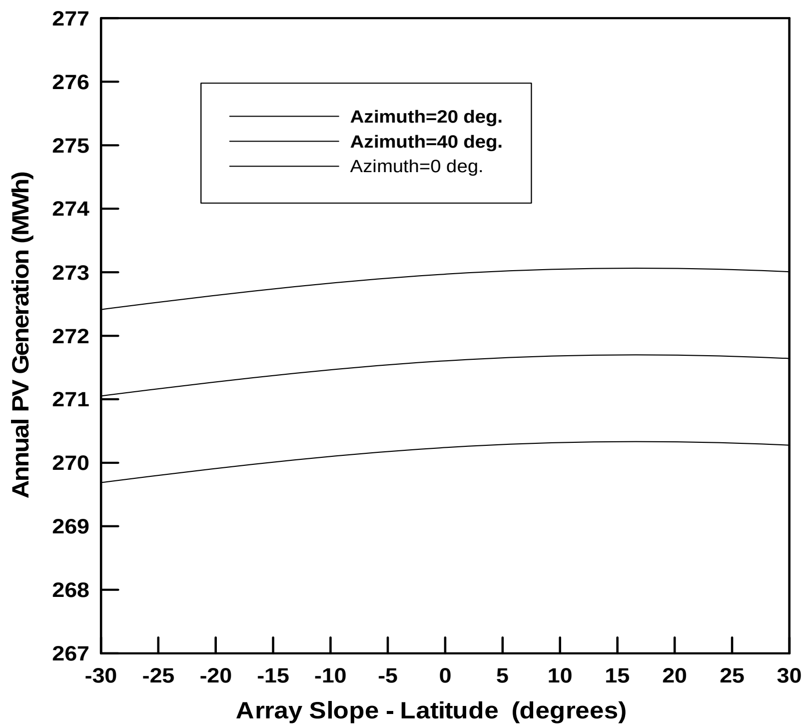

Figure 6: Variation of annual energy generation with array slope and azimuth angle

Figure 7 shows the yearly load in the building for different consumption components in 2012, after all energy conservation measures are implemented. About 23%, 31.5%, and 45.5%, of the total load are used for lighting and equipment, chillers, and HVAC auxiliaries, respectively. The figure shows that the lighting and equipment load can be completely covered by the proposed BIPV system.

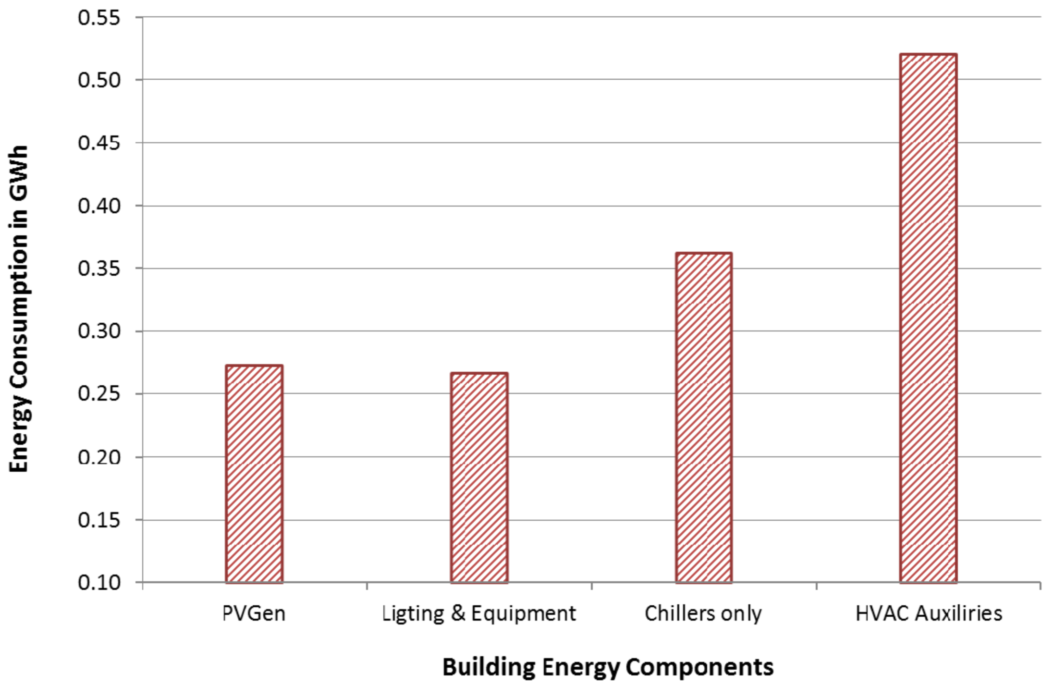

Figure 7: Annual load of the different consumption components in the building.

6.4 Cost Analysis and Environmental Impact of the PV system

The overall benefit of BIPV systems over conventional electricity sources can be demonstrated also by calculating energy returns on investment, energy payback times and net energy balances. The Energy Payback Time (EPT) of a PV system is the time (in years) in which the energy input during the module life cycle is compensated by the electricity generated with the PV module. The energy payback time depends on several factors including cell technology, PV system application and irradiation. The variation of EPT for the proposed BIPV system with tilt angle at fixed azimuth angle (azimuth=0°) is presented in Figure 8. This figure suggests that employing tilt angle of 40° (i.e. array with a slope of 10° greater than latitude) gives the best EPT which is approximately 8.7 years i.e. less than 9 years. These results indicate that the BIPV system can produce net or free power after 9 years of its operation. It is observed that the array orientation (40°) that maximizes the energy output of PV array is also minimizes energy payback time.

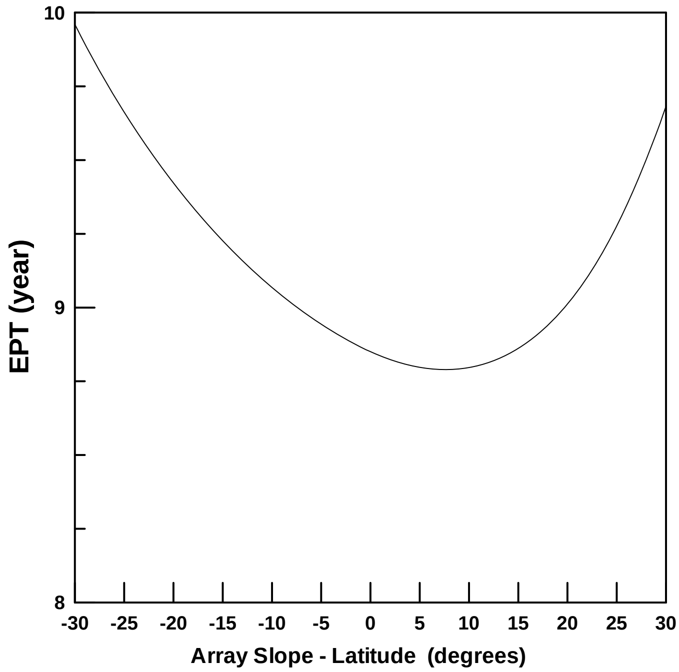

Figure 8: Variation of EPT with tilt angle at fixed azimuth angle (azimuth=0°)

The accurate analysis of the total avoided emissions for PV systems, should take into account the emission generated in the fabrication phase of the BIPV system components. The information about contaminating emissions in the production and installation stages of PV systems is practically not available since these systems are not currently manufactured in Kuwait. However, CO_2 emission rate from BIPV systems is much lower than the CO_2 emission rate from conventional utility and can be neglected. The variation of annual avoided CO_2 emission with tilt angle is presented in Figure 9. Again, the figure illustrates that the optimum tilt angle which maximizes the avoided CO_2 emission is 40°. At this angle, the avoided CO_2 emission is found to be more than 160 tone/year.

In addition, the costs due to the application of Kyoto Protocol, which penalizes the emissions of green house effect gases, fundamentally CO_2, should be added to the costs of conventional energy resources. In spite of the fact that Kyoto Protocol is not currently applied in Kuwait, however considering application of this protocol will enhance the economical and environmental aspects of BIPV systems much more. Application of Kyoto Protocol will force various productive sectors specially electrical and industrial sectors to pay for CO_2 emissions making BIPV systems more feasible in Kuwait climate.

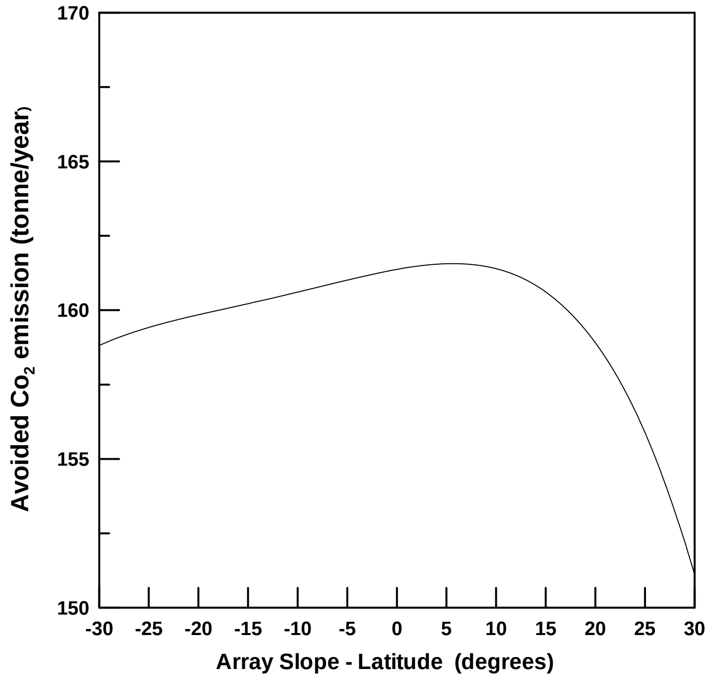

Figure 9: Variation of annual avoided CO_2 emission with tilt angle

7. Concluding Discussion

Gradual implementation of the first and second phases recommendations (without applying the chillers operation strategies and the lighting improvement outlined in phase-2) yields considerable energy savings as it reduces the annual building energy consumption from an average of 4.44 GWh (between 2005 and 2009) to about 1.56 GWh in 2011 as recorded by the building meter. This reduces the EUI from about 632 to 222 KWh/m^2 which is close to the lower limit of the international standard (171 KWh/m^2; Energy Information Administration, 2003) and far exceeds the local practical limits of some office buildings (315 to 410 KWh/m^2). The low EUI of the considered building compared to the local office building may be attributed to few reasons such as the low window to wall ratio of the building under consideration, heavy building construction, and partial use of the institutional building during summer semester and summer vacation.

The recommended lighting improvement in phase-II is not applied yet and recently the operation strategies of the chillers have been applied but the meter reading for 2011 did not account for it. Annual savings due to these two measures is predicted to be about 0.508 GWh which reduces the annual energy consumption to about 1.052 GWh (equivalent EUI of about 150 KWh/m^2). This further improves the energy consumption of the building to acceptable low value and concludes the energy conservation phases.

In order to move forward towards a NZEB, more efficient equipment for HVAC needs to be considered. For instance centrifugal chillers have explicit advantages over reciprocating chillers as they have almost double the average COP and much higher COP at partial loads. Replacement of the existed chillers will lead to increase the average COP from about 2 to more than 4 (ASHRAE Standard 90.1; 2007) which is reflected on an energy saving of more than half the current chillers consumption, i.e. 0.160 GWh. In addition, improving the HVAC auxiliaries may lead to a considerable energy saving of about 0.1 GWh. This will lower the

annual consumption of the building to only 0.792 GWh in comparison with 4.44 GWh in the years of 2005 to 2009 and 1.15 GWh in 2012.
Integration of the PV modules in buildings results in energy generation of about 0.273 GWh annually. This left an annual energy required of about 0.519 GWh which should be supplied using conventional sources.
The ongoing research on solar cells claims fast developing with respect to higher efficiency and lower cost. Nowadays, the laboratory scale solar cells reach efficiency up to 40% (Atwater, 2008). The higher efficiency along with the lower cost will enhance the power generated by the PV modules and make the use of PV more feasible in the near-term future. Alternatively, with the current used PV efficiency, the area required to balance the power should be increased. In this case, the façade area of the building can be utilized. Moreover, other sources of renewable energy may be adapted depending on the building circumstances.
In conclusion, the forgoing discussion indicates that the mid-size existing buildings can be converted into NZEBs or nNZEB and the decision may depend on the investment required for the conversion.

Conclusions

This work evaluates the outcomes of energy auditing, energy conservation and energy generation, using photovoltaic modules, on an existing institutional building in a trial to convert it into a net zero energy building (NZEB) or near net zero energy building (nNZEB). The performance and environmental aspects of the building energy conservation and the building integrated photovoltaic system (BIPV) in Kuwait are investigated. Based on the actual meter readings of the building consumption and the simulation results reported in the present study, the following conclusions can be drawn:

- Preliminary energy audit of the building results in an annual energy saving of about 290 MWh which is equivalent to 6.5% of the building consumption without the need to any retrofitting or investments.
- Detailed energy conservation with reasonable investments yields an annual energy savings of about 2.458 GWh which is equivalent to about 55.4% of the annual building consumption. The majority of energy saving is due to better operation strategies and fine control of the HVAC system.
- Efficient operation strategies can reduce the energy consumption of the chillers by about 21.5% which is equivalent to 9.2% of the building energy consumption.
- Efficient energy conservation can play an important role in converting the existing buildings into nNZEBs as it saves annual energy consumption of the building that is twelve times the energy generated by the PV modules.
- The performance of BIPV systems is greatly influenced by the variation in both array slope and azimuth angle.
- The integration of PV modules into the building produces about 27% of the building energy consumption and can cover the lighting and equipment load in the building. The optimum BIPV can avoid CO_2 emission of about 160 tone/year.

- Costs of PV modules and related equipment are expected to decrease considerably in the near-term future. Also, the efficiency of the PV modules is improving over the years. These factors will make BIPV systems cost-effective in the near future.
- Nearly NZEB can be achieved in existing buildings by re-commissioning the building, installing better performance HVAC systems and other equipment and integrating efficient PV modules.
- The results of the present work should encourage governments for wide installation of solar energy systems to keep our environment healthy and clean.

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Review of EU airport energy interests and priorities with respect to ICT, energy efficiency and enhanced building operation

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Abstract:
This paper gives an overview on EU airport energy interests and priorities with respect to ICT, energy efficiency and enhanced building operation. To achieve this objective the paper begins with an overview on airports role on energy consumption, then novel review of airport energy consumption figures and energy efficiency actions at the EU level is presented. The research covers also interest and requirements of two Italian airports (MXP and FCO) in relation to enhanced operation which include: sub-metering and visualisation needed to better understand the end energy use, data analysis for benchmarking and correlation with operational and weather data, action management for maintenance operation support.

Keywords:
Airport, Energy Consumption, Operation and Maintenance,

1. Introduction

Airports are actually small cities. They serve as critical nodes in the global, national and local transportation infrastructure connecting people, facilitating business, and enabling commerce. ACI EUROPE member airports (400+) welcome more than 1.5 billion passengers and handle over 17 million metric tonnes of cargo and 20 million aircraft movements (ACI-Europe, 2012).With respect to economic impact, Europe’s airports employ over 1.2 million people. These jobs alone with the amount up to a €59 billion have the impact on EU GDP and every on-site airport job indirectly creates another 2.1 jobs offsite (ACI-Europe, 2010). Correspondingly, airports are massive energy consumers and emission producers, being *de-facto* comparable to small cities. As one thinks of airports, they must be considered as open spaces containing many and various functional areas which include an “air side” (runway operations) and “land side” (terminal operations). These consist of runway spaces, runway lighting, hangers, maintenance bays, parking areas, outdoor lighting, terminal areas with their office spaces, check in areas, security areas, gates, restaurants, and shops amongst others. Therefore, due to the economic impact, their role as the critical transportation infrastructure nodes, and due to their energy consumption magnitude, the airports are excellent candidates for the energy efficiency research. Aviation’s overall contribution to the global GHG emissions inventory is dominated by aircraft in flight and these emissions are beyond the control and influence of airports. On the other hand, it is also true that still room is available to make advancements in decreasing GHG originated by airport buildings and services both in airside and landside facilities (Baumert, et al., 2005). Socially and in the terms of the scale magnitude, the energy efficiency improvements in this space are meaningful and support Europe towards its 20-20-20 and 50-50-50 policy targets. Airports are also adequate because they display an open and positive attitude about the efficiency measures arose from need, culture, and good business sense. In response to the arguably most difficult decade which the air industry has ever faced, airports and airlines are aggressively seeking for every possible cost savings measure. They also face pressure to “green” their image and politically there is the direct challenge from the government for transportation to be less dependent on the imported oil for security reasons. Thus the airport operators search for solutions (ACI-Europe, 2009).

CASCADE is a European FP7 research project which is developing facility-specific measurement-based energy action plans for the airport energy managers that are underpinned by Fault Detection Diagnosis (FDD) methods (PSE.AG, 2012). A framework and methodology for building customized ICT solutions is under development in order to integrate with and on the basis of the existing ICT infrastructure and operational procedures. A measurement framework and minimal data set will be established to control and benchmark the equipment performance, to optimize user behaviour, and to match client specifications. FDD enables the state-of-the-art energy management because it can be used to suggest problems in system design, equipment efficiency, and operational settings. CASCADE is aiming also at turning FDD into the actionable information by developing an energy action plan that links Actions-Actors-ISO Standards (ISO, 2011) through a web-based management portal. The developed ICT solutions will be able to integrate with existing systems and will target a 3-year return on investment and 20% reduction of energy consumption and 20% reduction of CO_2 emissions. CASCADE will achieve these objectives in time by:

1. Engaging the client, determining their needs, and encouraging organisational change
2. Integrating new ICT technologies with the systems present at client facilities
3. Collecting data on user operation and equipment performance
4. Applying fault detection methods across operational scenarios and equipment performance benchmarks
5. Making an Energy Action Plan that links actors, actions, and ISO standards based on facility specific data and providing cost/benefit (kWh, CO_2, Euros).

CASCADE approach focuses to the actions which airports can take in order to address GHG sources within their control and influence, fully in the line with ACI guidelines and recommendations for the future strategic airport planning and management (ACI, 2009). Energy management actions in large organizations, such as airports, span across different levels from the top level with the overall energy policy and planning to the bottom with scheduled and emergency based operation and maintenance. In order to support top level energy management it is important to better understand the starting point of an airport in relation to its energy consumption and set reasonable targets. The work presented in Section 2 shows an analysis of energy trends and energy efficiency interests of EU airports in broad terms are very relevant. This analysis is unique and novel by itself since it is the first airport specific study done in this direction. The paper documents also the study of two important European airports Roma Fiumicino (FCO) and SEA Malpensa (MXP) describing their current requirements in terms of enhanced airport operation which were identified in close collaboration with airport staff to answer their expectation in terms of energy savings, plant operation optimization and organizational questions towards an ISO based Energy Management (Section 3).

2. Review of airport energy consumption figures and energy efficiency actions at the EU level

2.1. Methodology

This study is based on the collection and comparison of both energy figures along with energy action measures of airports with the European area. In terms of population and sampling, as can be seen in Fig. 1 below, airports were gathered from the ACI – Europe monthly passenger traffic report 2010 (ACI-Europe, 2010b) specifically from the list shown for the accumulated passenger traffic (January-December 2010) which comprised of 93 airports (this is the total number of airports that was provided with yearly traffic data form ACI Europe in the annual report). Secondly, the airports which have become Airport Carbon Accredited (ACA) were considered which accounted for 57 airports. Some of these were already included in the previous 93, giving us a total of 113 airports for analysis. Fig. 1 shows the geographical extent of the sample taken. It must be noted that airports like Moscow and Istanbul-Ataturk have been included in this study, since they were included in the ACI Europe annual report. The two airports are in the geographical and economic influence of the European aviation community.

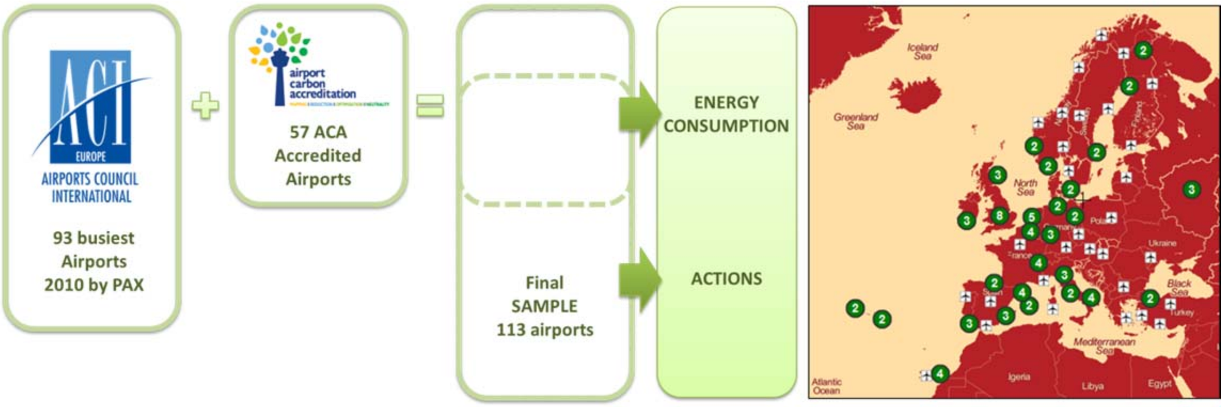

Fig. 1. Population definition and location

The collection of information took place during the period of October 2011 and May 2012. The sourcing of this information was done through the official websites of the airports themselves on the internet and in some cases through the websites of concessionaires or airport operators, thus all used figures are publicly available. The percentage of available data from the global sample of 113 airports can be seen in Fig. 2 below. Almost half of the airports did not disclose any energy figures for 2010 (55 out of 113). It must be noted that some airports have been included in aggregated figures making it impossible to gather specific information about one single airport, i.e. Swedavia for Swedish airports. Considering only ACA accredited airports the availability of energy figures for was higher and equal to 65% (37 airports out of 57 accredited).

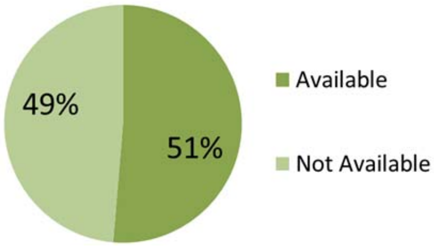

Fig. 2. Energy figures – data availability for 2010

An interesting finding was that a number of smaller airports which are included in bigger organisations with larger groups of airports (e.g. TAV Airports Holding - the leading airport operator in Turkey) benefit from the general policies and environmental action plans which exist at the large organisation level but wouldn't likely exist for a same size airport only locally managed. For example, Flores airport (FLW) with only 42,446 passengers in 2010 publicises good quality information. Portuguese airports (Aeroportos de Portugal, ANA) are a great example of one of the common cases throughout this investigation. This is the inclusion of a number of different airports in one single report under a common management. This can vary from state run companies to big contractors, e.g. British Airport Authority (BAA). The difficulty with this is that the figures are reflecting the environmental performance of the company's activities making it difficult to get individual performance data for one single facility. This sort of reporting has minimised the total number of data which could have been used during the study to enrich the sample. It also highlights the need for a consistent and standardised format for accountancy and reporting of energy consumption figures.

Different components for energy consumption (end use) exist within the airport environment. The reporting of these sources varies greatly from total energy demand figures which have been clearly broken down into further categories of energy consumption (e.g. by facility, by end use) with other reports including only one energy consumption figure with no clarification of what is included.

Taking into account all airports in the sample with energy consumption (energy end use) figures, the analysis has considered only the total energy consumption given by the formula Equation 1. Note that fuel does not include back up units and/or ground transportation.

Equation 1: Energy Consumption Calculation

$$\text{Energy Consumption} = [\text{gas}+\text{electricity}+\text{district heating \& cooling}+\text{fuel}] - [\text{sold energy}]$$

2.2. *Energy figures*

Among the considered 113 airports set, only 58 had figures for their total energy consumption (energy end use) available for either 2009 or 2010.As described in section above all data sources are publicly available. As we can see in Fig. 3, Fig. 4 and Fig. 5, a correlation exists between the airport energy consumption and both the number of passengers and the traffic unit. To account for the passenger number, we have used the ACI definition of "PAX" described as follows:

Equation 2: Definition of PAX

$$\text{PAX} = [\text{international passengers} + \text{domestic passengers} + \text{direct transit passengers}]$$

International and domestic passengers take into account both enplaned deplaned passengers. Direct transit passengers (who arrive at and depart from the airport on a flight bearing the same number) are counted only once. American Aviation industry uses the number of enplanements as a consistent indicator in relation to passenger numbers. This would make it easier to aggregate airport passenger numbers and to work out individual airport contributions and weighting factors which could be used as a basis for more in depth analysis. For our analysis, we have used the “traffic unit” as a comparable metric. The “traffic unit” (tu) is used internationally and is suitable for assessing airports based on both the number of passengers and the amount of freight (*1 tu = 1PAX or 100kg Cargo (incl. mail)* (Both enplaned and deplaned).

Additionally there are a number of different factors which surely impact on airport energy consumption and could subsequently result in further interesting studies, for which more data would be needed. These include factors such as:

1. Airport size (area and volume of conditioned spaces, area of externally exposed building envelope)
2. Shape factors:
    a. Compact (One main Building with bus transportation)
    b. Pier finger terminals
    c. Pier satellite terminals
    d. Remote satellite terminals
3. Location-Climate (Hot and cold degree days – HDD and CDD, solar radiation, humidity levels)
4. Hours of Operation
5. Building envelope
6. HVAC Systems and Controls
7. Level of maintenance at the facility
8. Occupant / User behaviour and energy management

It was not possible to incorporate these parameters into our analysis due to time constraints and other limitations such as consistent availability of data for the whole sample.

In Fig. 6 below, the normalised energy consumption has been plotted against the Total energy consumption, where the size of the circles represents the number of PAX. As this is the case that the circle size is the PAX, it gives you an idea of how busy is an airport is and their impact with regards to energy and normalized energy consumption.

London Heathrow (LHR), Paris Charles de Gaulle (CDG) and Frankfurt (FRA) are clearly ahead of the rest in relation to their overall energy usage, but with 13.57, 17.93 and 15.69 normalised energy consumption respectively, they are almost one and a half times the average of 9.29 kWh/PAX year.

Just over 74% of the 58 sample airports with available data are below this benchmark figure of 9.29 kWh/PAX year. The other 26% include airports such as Rovaniemi Airport (24.9), Milan Malpensa (20.91), Ivalo Airport (18.39) and a very high 53.215 kWh/PAX year for Enontekio Airport. The reason for the large numbers result due to a number of different variables (including variation in PAX traffic and/or airports may have large volumes of freight traffic). Enontekio has only a mere 17,683 PAX/year but consumed just over 1 GWh in 2010. Rome Fiumicino was responsible for just 7.23 kWh/PAX during 2010, 2.06kWh/PAX below the benchmark.

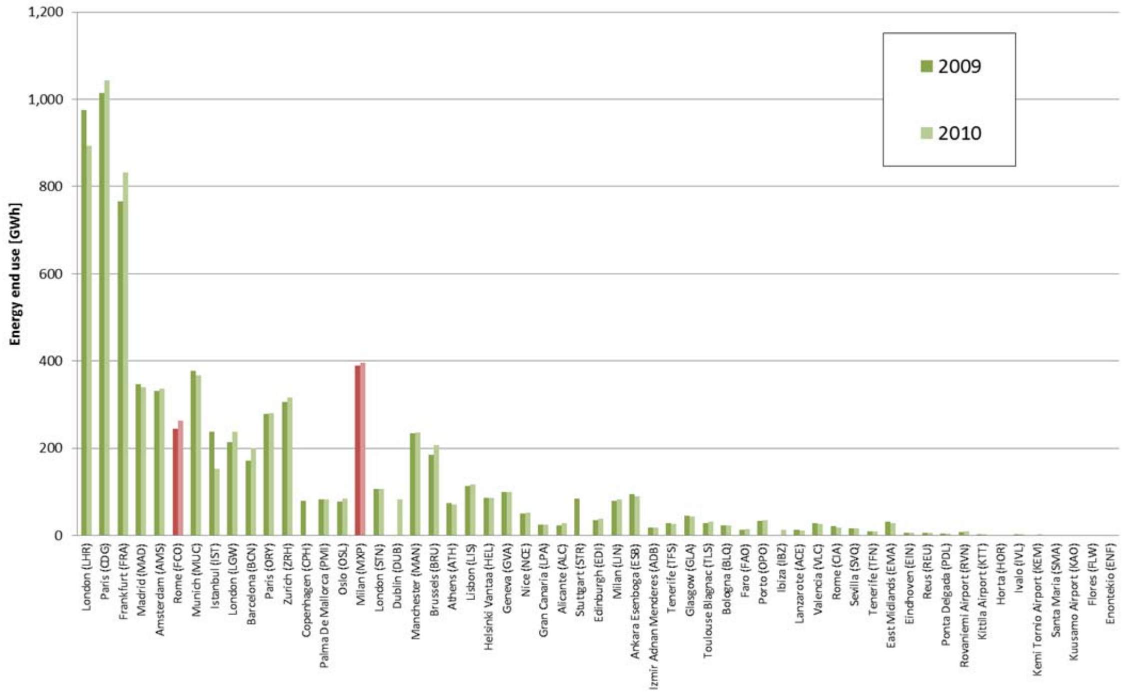

Fig. 3. Energy end use in 58 airports ordered by number of yearly passengers

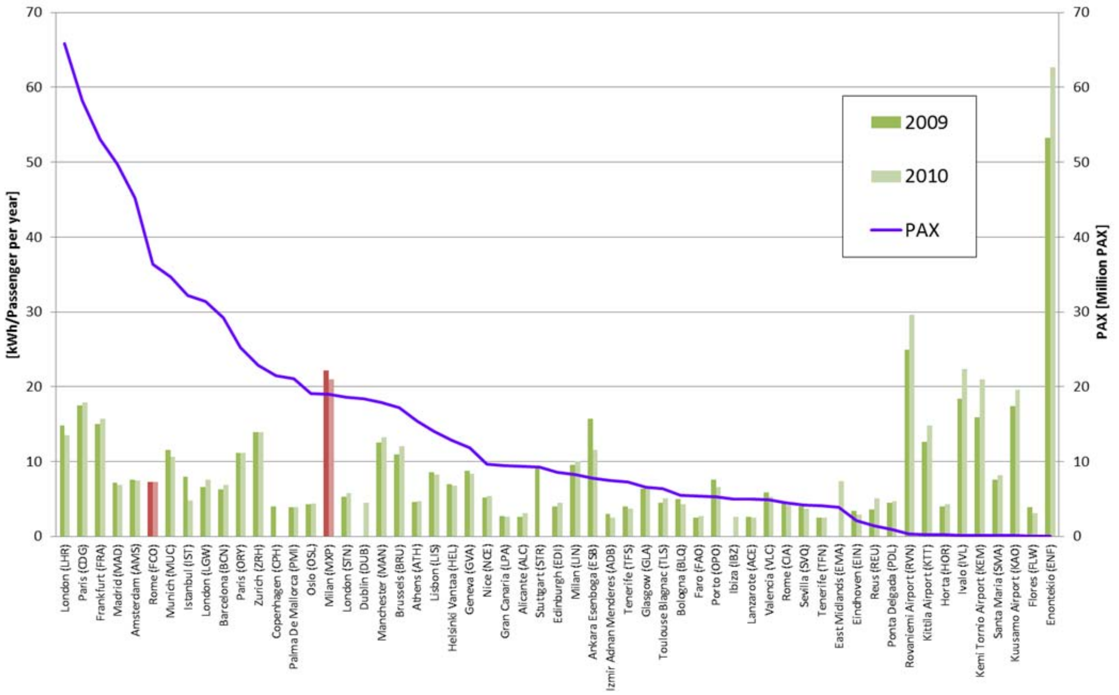

Fig. 4. Normalised Energy Consumption by Passengers figures

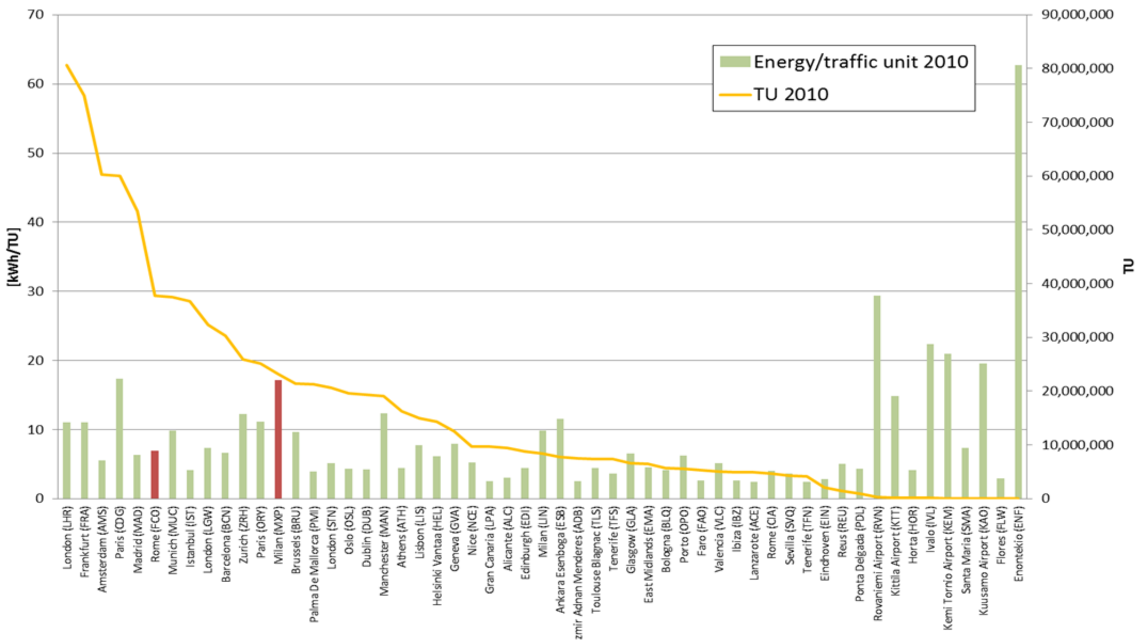

Fig. 5. Normalised Energy Consumption by Traffic unit [TU]

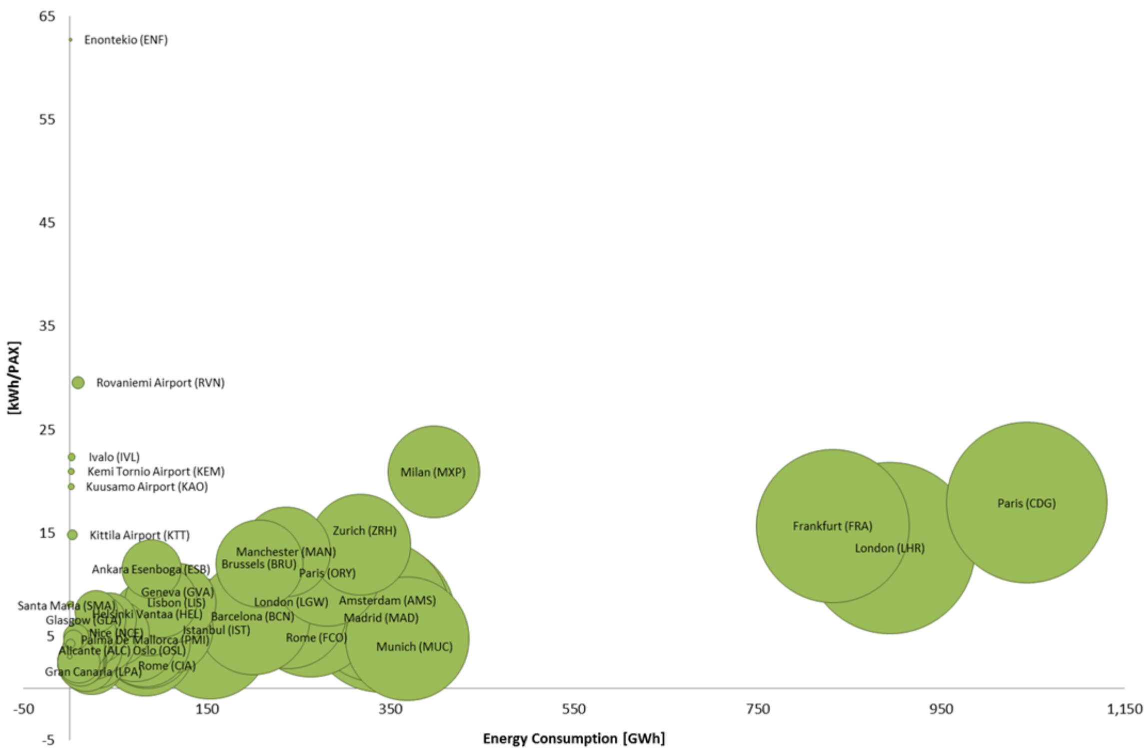

Fig. 6. Total Energy Consumption [GWh] vs. [kWh/PAX] (where size of bubble represents PAX)

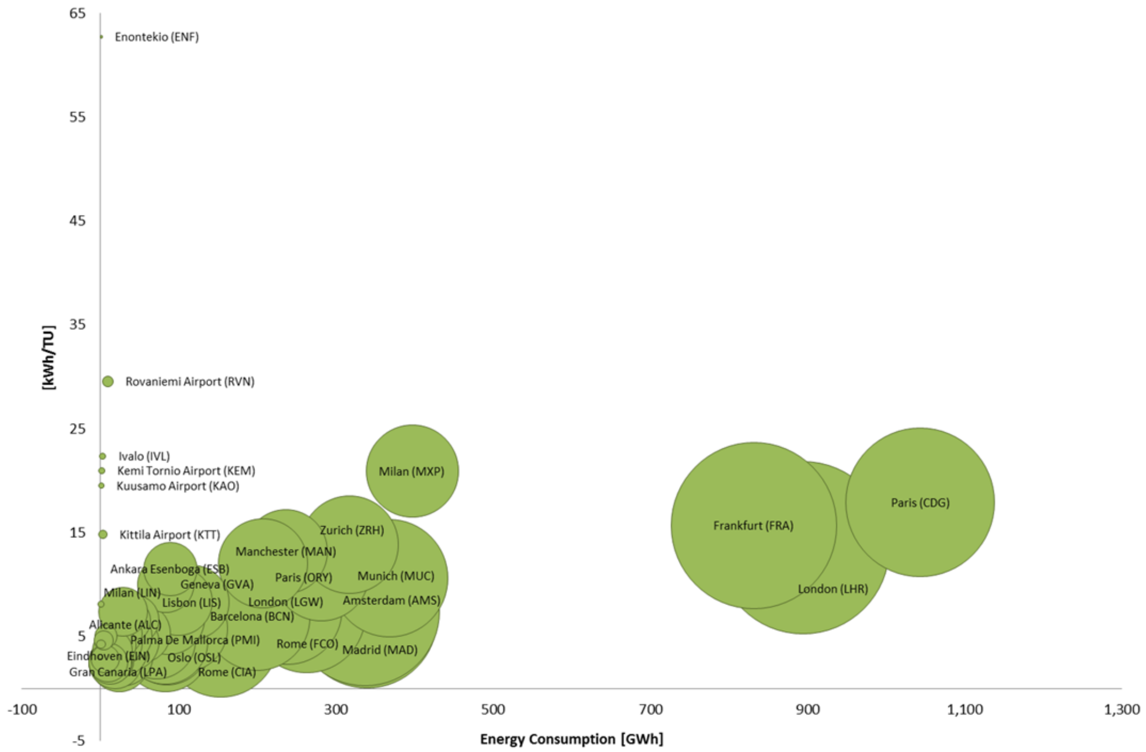

Fig. 7. Total Energy Consumption vs. Energy Consumption per TU (where size of bubble represents PAX)

2.3. Energy actions and interests

All related actions reported in our 113 Sample airports during the period of 2009-2010 have been gathered and analysed. A number of airports do not have any significant action in 2009-10 because they were built or refurbished just before the considered period. The total number of energy related actions that it was possible to identify from the available information across 113 was 302. The actions were grouped in 5 different categories: energy management, HVAC, lighting, Renewable Energy Technologies (RET) and operational procedures. The following sections give a description of each category with some example for different airports.

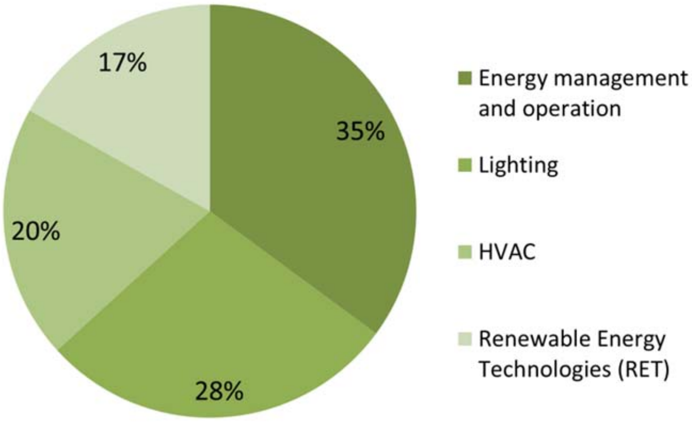

Fig. 8. Energy actions per category

Energy management and operational procedures

The most popular category was “Energy Management and operational procedures with 106 out of 302 actions. When it comes to energy saving, energy management is a sustainable way to achieve goals set out by an organisation, not only for achieving cost savings but also other rewards such as a productive and enthusiastic workforce, (as encouraged in ISO 50001). Until recently, many organisations did not place a big focus on having an energy management program implemented at their facility. This trend is changing rapidly, and energy management is becoming a necessity for cost efficient operations. The integration of sustainability into daily operations and decision making processes needs to be strongly emphasised (ISO, 2011).

- Expansion of systems for central operations monitoring of boiler and power controls
- Environmental training
- Installation of additional metering for controlling major consumption points
- Integration of additional metering with existing Building Management Systems
- Replacing all oil vehicles with electric Powered vehicles
- Lower aircraft average taxiing time by 10% by 2015
- Power sources provided at Gate as opposed to using APU
- Shutdown of Baggage handling systems when not in use

Lighting

As shown in Fig. 8, lighting actions made up 28% of the total energy related actions gathered throughout the study. With potential electricity savings of 85%, LED lighting refurbishments presented themselves as the most a common energy saving measure with examples including replacement of runway fixtures to LED, motion sensors for automated control of lighting areas which may not be used very frequently. Passive Infrared sensors (PIR sensors) were used in many cases. These are electronic devices that measure infrared (IR) light radiating from objects which come into its area of detection. Motion is detected when an infrared source with one temperature, a human, passes in front of an infrared source with another temperature, such as a wall.

- Motion detection for lighting
- LED Replacements
- Intelligent Lighting controls for areas of low occupancy EG. Passive Infrared Sensors (PIR)
- Retrofit of 65000 light fittings with Retrolux system (reduction of approx 20W per fitting)
- Roof glazing replacements
- Passive Lighting

HVAC

Heating Ventilation and Air Conditioning (HVAC) can be responsible for up to 80% (SEAI, 2008) of a facilities energy bill, due to poor design, operation and management. The most frequent measure taken in relation to HVAC was the installation or improvement of BMS and BAS systems. BMS and BAS schedules were also manually optimised according to effective user profiles.

- Regulation of ventilation on new generator at arrival
- Installation of air curtains in boarding bridges
- BMS/BAS system improvement
- Optimisation of setpoints, e.g. Setting AC systems to OFF on weekends or Off peak
- Installed frequency converters on two ventilation systems
- Cold and Heat Storage (CHS)
- Combined Heat and Power (CHP), Tri Generation Plants

Renewable energy technologies

Only 17% of all actions came under the category of renewable energy. The most adopted RET systems were:

- Photovoltaic panels
- Biomass fuel production
- Geothermal
- Wind power

3. Airports requirements for enhanced operation, the specific case of MXP and FCO airports

This section shows both the core airport needs in relation to enhanced airport operation with a specific focus on energy action management and HVAC systems. This work is the result of many iterations with airport stakeholders of both Milan Malpensa airport (managed by SEA Spa) and Rome Fiumicino airport (managed by ADR Spa) to determine their interests and priorities with respect to energy efficiency and with CASCADE consortium partners (technology providers) to determine high impact strategies that must be targeted to work within the limited resources and time of the project. The aim of this section is to give an overview of gaps for improvement identified within current airports energy and maintenance operation. The main needs identified on the airport side were the following:

1. Energy savings and CO_2 emission reduction
2. Hardware and software for sub-metering at every level and location within the whole airport
3. Identification and advanced visualisation of Key Performance Indicators (KPIs)
4. ISO 50001 certification
5. Correlation studies between measured parameters (operational & weather data vs KPIs)
6. Maintenance activities support (performance assessment, costs impact, workflow and action management, predictive maintenance, etc…)

We will focus now on the two main areas in which we identified room for improvement: performance monitoring and energy and maintenance action management:

3.1. Performance data monitoring

Both airports do not have a detailed energy end use monitoring system. Available measurements data on the thermal side are only at the overall airport level (utility bills) whereas on the electrical side they are only at the main switchboard level by which is possible to identify energy consumption of different macro areas (like terminals or buildings) or main systems (like BHS) of the airport. This resolution doesn't allow for end use energy monitoring and performance assessment. The first airport requirement is therefore sub-monitoring at a higher resolution and deeper level of detail, closer to end use energy consumption (e.g. HVAC air handling units and components, lighting for specific indoor or outdoor spaces or other equipment electrical/thermal consumption). Once more data is available also advanced visualisation is required. Another requirement is to identify representative KPIs at both facility and system/subsystem level. Correlation studies need also to be carried out between KPIs and relevant parameters available such as weather conditions (outdoor air temperature, relative humidity, solar radiation wind speed, etc…) and operational data (flight numbers, passengers, baggage and freight movements, etc…). Correlation studies are very useful for performance assessment, benchmarking and facility level fault detection. Currently at MXP a daily energy consumption monitoring review is carried out to compare available electrical energy consumption with the consumption of the day before of the same day in the previous year. At FCO this is done only on monthly basis. CASCADE has the potential to offer to both airports a significant opportunity of improvement through advanced visualization techniques and correlation between energy use and the parameters with major influence on energy consumption.

2010	GIORNO			mercoledì 06-ott-10		
	TOTALE SEA1 + SEA2		h	310.538,40 kWh		
	IFF. GIORNO PRECEDENT		-2,32%		-8.620,71 kWh	-2,70%
	MEDIA GIORNALIERA		h	12.939,10 kWh		
DIFFERENZA TRA ANNI				0,98%		
2011	GIORNO			giovedì 06-ott-11		
	TOTALE SEA1 + SEA2		Wh	313.577,88 kWh		
	IFF. GIORNO PRECEDENT		-0,15%		6.702,62 kWh	2,18%
	MEDIA GIORNALIERA		h	13.065,74 kWh		
			Diff. %	kWh	Diff. kWh	Diff. %
TERMINAL 1	Aerostazione	Cabina 16	2,42%	14.443	303	2,14%
		Cabina 17	0,35%	25.119	1036	4,30%
		Cabina 18	-0,90%	37.618	61	0,16%
	BHS	Cabina BHS-I	-3,34%	8.635	304	3,65%
		Cabina BHS-S	-1,23%	9.967	117	1,19%
	Sat. A	Cabina 15	-2,24%	25.372	274	1,09%
	Sat. B	Cabina 14	-1,12%	23.225	1243	5,66%

Fig. 9. Screenshot of automatically generated energy consumption daily report at MXP.

3.2. Energy and maintenance action management

Both airports use SAP software platform for enterprise management. This platform also allows for energy and maintenance action management, Fig. 10. shows the current actions work flow at FCO: if a fault or an operation problem is detected by either a room occupant or the control room (though the BMS supervisory interface), a corrective action is assigned to the external maintenance company though the SAP call centre (outsourced service) or though directly into the SAP system (by the control room). The only difference with MXP is that in the Milan airport case there is not call centre and all the corrective actions (and user complaints) pass through the control room and form there they are directly entered into SAP. Once the corrective action is entered in the system, the outsourced maintenance company automatically receives a printout with the corrective action request. This action is then carried out by the maintenance company and once it is completed, it is closed on the SAP platform. However, the current version of SAP at both airports doesn’t allow the airports to formally validate the closure request coming from the maintenance company. This leads to possible issues like: the maintenance company doesn’t close the action as expected by the airport or doesn’t really specify all the details of the work carried tout to fix the issue. This feature could be automated in the CASCADE solution platform in relation to the actions triggered by the FDD providers. Airports would like to have a platform that allows a systematic way to plan maintenance related actions including basic finicalities like task and responsibilities assignation to people and time planning but also advanced functionalities like considerations on actions related energy savings, implementation costs and payback period calculation. Another aspect is that there is a lot of paper work involved once the fix is carried out by the maintenance company and this is all paper based, this is also something that the airports would like to automate and systematise possibly within the CASCADE. Lastly, in the airports wishes list there is also a tool feature to support the negotiation process between airport maintenance administration office and the outsourced maintenance company which initiates whenever actions involving additional costs need to be carried out.

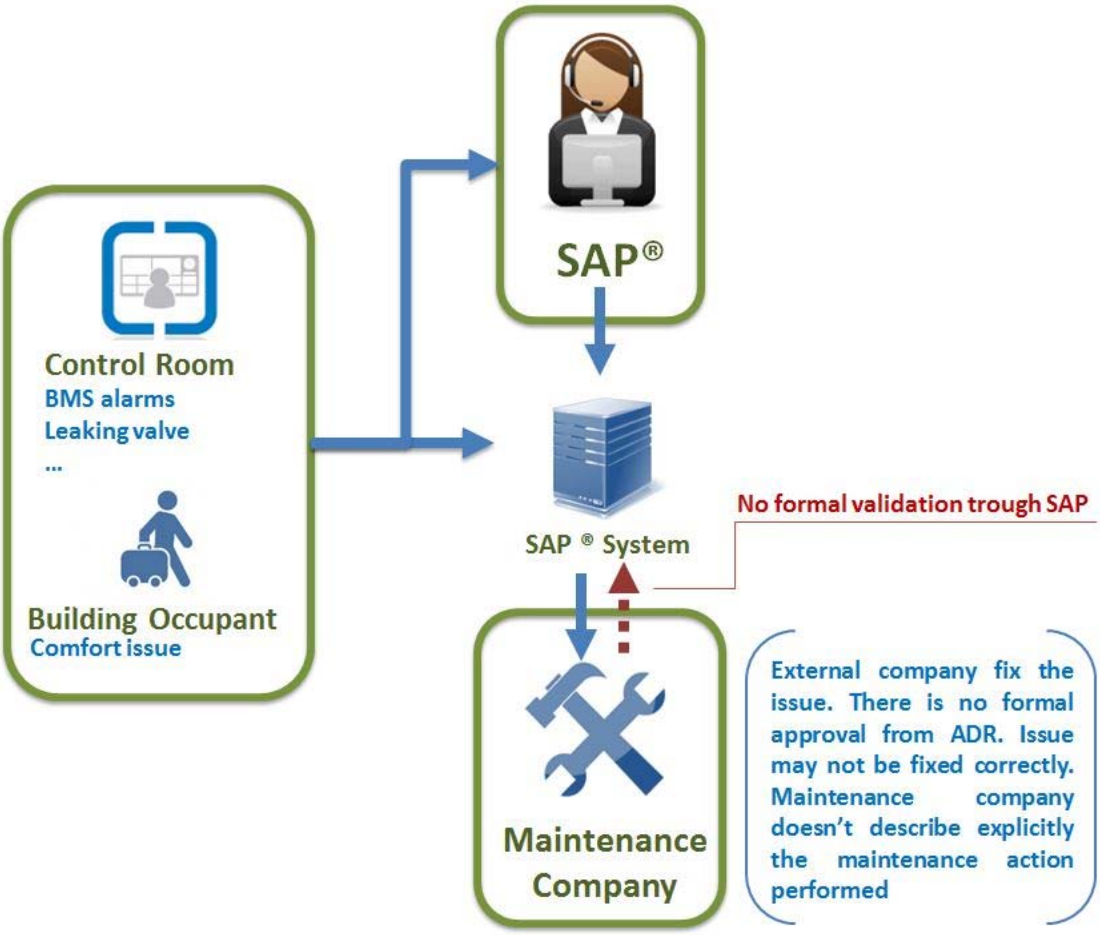

Fig. 10. Energy and maintenance action management workflow

4. Conclusion

This paper gives an overview of airports role on energy consumption at the EU level and the importance of research in this field. An overview of the FP7 CASCADE project is also given in the introduction. The issue of enhanced airport operation is tackled at both top and bottom level. In relation to the top level analysis a novel and detailed research of available airport energy consumption figures, energy actions and interest of the top 113 EU airports. In relation to the bottom level, the case of two airports is presented. This section reviews FCO and MXP operation and describes current requirements in terms of enhanced airport operation which were identified in close collaboration with the airports to answer their expectation in terms of energy savings, plant operation optimization and organizational questions towards an ISO based Energy Management. The identified airport requirements for enhanced operation include: sub-metering and visualisation needed to better understand the end energy use, data analysis for benchmarking and correlation with operational and weather data, action management for maintenance operation support.

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Bio-Climatic Analysis and Thermal Performance of Upper Egypt "A Case Study Kharga Region"

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ABSTRACT
As a result of the change and development of Egyptian society, Egyptian government has focused its attention of comprehensive development to various directions. One of these attentions is housing, construction and land reclamation in desert and Upper Egypt. In the recent century the most attentions of the government is the creation of new wadi parallel to Nile wadi in the west desert. Kharga Oasis is 25°26′56″North latitude and 30°32′24″East longitude. This oasis, is the largest of the oases in the westren desert of Egypt. It required the capital of the new wadi (Al Wadi Al Gadeed Government). The climate of this oasis is caricaturized by; aridity, high summer daytime temperature, large diurnal temperature variation, low relative humidity and high solar radiation. In such conditions, man losses his ability to work and to contribute effectively in the development planning due to the high thermal stress affected on him. In designing and planning in this region, it is necessary not only to understand the needs of the people but to create an indoor environment which is suitable for healthy, pleasant, and comfortable to live and work in it. So, efforts have been motivated towards the development of new concepts for building design and urban planning to moderate the rate, direction and magnitudes of heat flow. Also, reduce or if possible eliminate the energy expenditure for environmental control. In order to achieve this, attention has to be focused on building design to improve its thermal performance, which is a function of building form, orientation, location, and materials used and produce comfortable environmental conditions without increasing of energy consumed. This can be valid in three stage, the first one by using the bio-climatic analysis, the 2nd one by the handle and simplified calculation methods (U-value, Thermal time constant, and Degree day), and the 3rd one is by the simulation method. The admittance procedure is a technique for estimating cooling/heating load and temperature changes under cyclic conditions by using the thermal characteristics (Y-value, λ, φ, Sf) of the building structure. It dependent on determining the daily means value and the swing about the mean. The admittance method is used and a computer program is developed to predict the heating and cooling load as well as the environmental air temperature by the author. This study deals with the bio-climatic analysis and thermal performance of building in Kharga Oasis. The results show that, the air catcher, court and Passive cooling systems (evaporative cooling), maintained the indoor climate in the thermal human comfort zone during the hottest period under the effect of climatic conditions of Kharga. Also shading devices, and suitable orientation achieve a harmony building with environment. Using insulating materials in exposed walls and roof save energy by about 60%. The Thermal insulation thicknesses between 0.03-0.05m for exposed walls and 0.05m for exposed roofs are suitable to valid the required thermal resistance in Kharga Oasis according to the Egyptian Residential Buildings Energy Code, ECP 306-2005.

Keywords:
Admittance, building envelope, cooling and heating load, Kharga Oasis, thermal performance

1. Introduction

El-Kharga Oasis (*Al-Kharijah)* is the southernmost of Egypt's five western Oasis. It is located in the westren Desert, about 200 km to the west of the Nile valley, it is the capital of New Valley Governorate (Al Wadi Al Gadeed). It is located 550 kilometers to the south of Cairo. Kharga Oasis is 25°26′56″north latitude and 30°32′24″east longitude. This Oasis, is the largest of the oases in the westren desert of Egypt and consists of a depression about 160km long and from 20km to 80km wide. The Kharga Oasis must be one of the most beautiful places in the world, especially at sunset; everything you see at this "green island in the middle of a yellow ocean of sand", is natural. Whether, you are sleeping under the stars, or just relaxing between the high palm-trees, you will find a feeling of integration with the environment. Kharga is the most modernized of Egypt's western oasis. The main town is a highly functional town with all modern facilities, and virtually nothing left of old architecture. There are extensive thorn palm, acacia, buffalo thorn and jujube forests in the oasis surrounding the modern town of Kharga. Although the Kharga Oasis occupies around one third of the whole lands of Egypt, it contains the least population density in the whole nation with around 20,000 inhabitants nowadays and a population density of 4 persons in each square kilometer. The reason behind this is the vast areas of the deserts surrounding the Kharga Oasis.Tourism is not considered a major activity for the people living in Kharga. Most of the people of Kharga work in normal jobs like the inhabitants of Cairo, Alexandria, and the other cities of Egypt and the other work with agriculture . Al Wadi Al Gadeed also hosts one of the largest phosphates mine in the world in the area of Abu Tartour. Kharga Oasis has many monuments and ancient sites such as; Temple of Hibis, Cemetery of Bagawat, Temple Of Ghweita, Temple of Qaser Al Zayyan, Temple of Dush in the Oasis of Paris and museum of Antiquities of Al Kharga [(1)]. Thermal comfort plays a vital and an important role for people to continue and chair in the development for their nation. Most of natural developing project lies in the desert to go out from the narrow valley which is about 5% of Egypt area. Where the climate of this region is caricaturized by; aridity, high summer daytime temperature, large diurnal temperature variation, low relative humidity and high solar radiation reaches to about 1000W/m^2 on horizontal surface in summer season. These extreme thermal environments reflected on people and their effort in development and sustainability due to the high thermal stress. So it is important to study and evaluate the effect of the external environment conditions on the thermal comfort for people in the open areas and in residential building in this region. Also study the effect of thermo-physical and optical properties of the building materials on saving suitable environmental condition inside building. Building envelope (walls/ roof) regards as the main construction element which has an important role in the thermal performance of unconditioned building and in saving energy in conditioned building. Where roof considered the major part of the building envelope, affected by the extreme weather, attention must be focused on roof. In Egypt different field measurements and theoretical studies were carried out to investigate the thermal performance of the traditional houses under the effect of local external climatic conditions of Cairo region (30^{o}N) [(2& 3)]. Theoretical and experimental study was carried out to investigate the thermal performance of a pre-fabricated concrete flat in 15 May city, Cairo, Egypt and the results investigate that reasonable agreement achieve between the theoretical and experimental indoor air temperature of the flat [(4)]. Saving energy consumption in hot arid region and the effect of nocturnal radiation in increasing the thermal efficiency of the building was studied theoretically under the climatic conditions of Aswan (24^{o}N) [(5)], Egypt. The requirement for building in the Waste Costal of Red See (Ghardaga) was carried out [(6)]. Evaluating the external climatic conditions of Toshky region (23.5^{o}N), Egypt and the thermal performance of some traditional building built their. This study shows that using Nobaa sandstone in wall alone is not favorable and didn’t valid thermal comfort due to the high storage, high thermal mass and thermal conductivity of it, also shows that domes or vault built from concrete without using material with special thermal characteristics is not the solution, and if dome hasn't top opening to loss the hot air, a hot heat island is found and led to discomfort [7, 8 & 9]. A developed new building material with three line defense of thermal insulation used in walls and apply the concept of domes and vault with good thermal insulation help in valid the thermal comfort in building in Toshky region, and let the indoor environmental condition of the building to be within the comfort zone in the very hot and dry period in summer [10]. The thermal performance of exposed composed roofs in very hot dry desert region in (Toshky) region, Egypt was carried out and investigate that; the construction roof systems (insulated concrete, double, planted and un-insulated concrete roofs) valid an indoor air temperature thermal damping of about 96%, 90%, 89%, and 76% respectively, the green roof gives the lower indoor air temperature, due to the evaporation process [11]. The thermal performance of building envelope in very hot dry desert region in Egypt (Toshky Region) was carried out and investigate that; the indoor air temperature of hollow clay brick and light sand block are nearest to the upper limit of thermal comfort [12]. Theoretical and experimental studies were carried out to evaluate the thermal performance of building with different building envelope in different country. The thermal performance of building and optimization the thermal insulation thickness in walls were studied [13]. The thermal performance of a vegetated cladding system on facade walls was also study [14]. Experimental approach to the contribution of plant –covered building envelops were study [15]. The effect of thermal mass walls to reduce building heating or cooling load where also studied [16]. In Mediterranean countries theoretical and experimental study was carried out to evaluate the thermal performance of building. The ventilating roofs have been widely used, the effect of roof tiles on the thermal performance of ventilated ducts were studied, and indicate that the presence of air permeable layer and elements to protect the ventilation duct eliminate any difference in performance which were due to the cross section of the ventilation duct [17& 18]. The finite element model was carried out to investigate the thermal performance of non air conditioned buildings with vaulted roof and flat roof. It clear that building with a vault roof have lower indoor air temperature compared to those with a flat roof , that is because such roof dissipate more heat by convection and thermal radiation at night due to the enlarged curved surfaces [19]. Different insulation materials (mineral wool, polyurethane, and polystyrene) were used to evaluate the thermal performance of building for decreasing the thermal demand and heating and cooling load [20]. Previously theoretical and experimental studies were carried out using different passive approach; shading, insulation, roof pond, movable shading, and evaporative cooling for roof [21-27]. Measurements and analytic work carried out under the climatic conditions of central Anatolia to provided valuable insights on the thermal performance of detached dwellings of traditional and contemporary construction [28]. With the energy crisis, efforts have been motivated towards the development of new concepts for building design and urban planning to moderate the rate, direction and magnitudes of heat flow and reduce or if possible eliminate the energy expenditure for environmental control. In order to achieve this, attention has to be focused on building design to improve its thermal performance and produce comfortable environmental conditions. This can be valid in three stage, the first one by using the bio-climatic analysis, the second one by the handle and simplified calculation methods (U-value, Thermal time constant [29], and Degree day [30]), and the third one by the simulation method. Where the simplest calculation method is not enough to give a limit of comfortable zone inside the buildings, but it may give a picture about the building energy consumed. The simulation method regarded the best method. There are many mathematical methods to solve the equations of heat transfer through the building envelope, from which the matrix method [31]. The admittance procedure using the matrix solution is used to estimating the energy transfers and temperature changes under steady cyclic conditions. It was developed by Danter and Loudon at the building Research Station [32 & 33], then used by Milbank and others to give the thermal characteristics (Y-value; Y, decrement factor; λ, time lag; φ , surface factor; Sf of multi-layer construction [34 & 35]. It determines the temperature dependent on the daily mean and swing about the mean. So a computer program was developed and prepared to calculate the heating and cooling load of a residential building in Egypt and also to predict the indoor air temperature. The program is dependent on the admittance method. This study deals with the evaluation of bio-climatic analysis of Kharga Oasis. Also investigate the effect of external climatic condition and thermo-physical characteristics and thermo-physical properties of building materials on the thermal performance of residential building to valid comfort and save energy according to Egyptian residential code[36].

2. Climatic Factor

The main factors affecting on studying the thermal performance of building are; the outdoor climatic condition (outdoor air temperature, relative humidity, solar intensity, and wind peed).

2.1. The Outdoor Air Temperature and Relative Humidity.

Figure (1.a) shows the monthly mean maximum / minimum of the outdoor air temperature of Kharga Oasis. The figure shows that the monthly mean maximum / minimum temperature increase gradually from January till reaches it's maximum value of about 40° C in May, June, July, and August and then began to decrease. The figure also shows the neutrality temperature and the upper/lower limit temperature of comfort in Kharga Oasis Eq.(1) and table (1). Figure (1.b) shows the monthly mean maximum / minimum relative humidity in kharga Oasis, it seems to be decreased gradually from January to reach minimum value in May and June then began to increase slowly. The minimum value in the monthly mean maximum relative humidity is about 15%. It is clear from the figure that through summer season in Kharga Oasis that the low value of relative humidity with the high value of dry temperature led to the importance of using evaporative cooling in Kharga Oasis in general and in building in special case to secure the thermal comfort for people[37].

2.2. The Solar Intensity Incident on Horizontal and Different Orientations

Figure (2) shows the variation of the computed solar intensity fallen on the horizontal surface and walls of different orientations on Kharga Oasis, during summer season (July, 21) according to Shaltout[38] and ASHREA, 1981[30]. The figure shows that the south orientation is the best orientations received minimum values of solar intensity during summer season and this help in making it easy to control the solar radiation falling on that orientation. The horizontal surface receives the greatest amount of solar intensity and its maximum value reaches 1071 W/m^2. Also the east/west direction receives high solar intensity with respect to the other orientations where their maximum values reaches 780 W/m^2. The figure clear the amount of solar intensity fallen on the north direction in the morning and afternoon where its maximum value reaches 210 W/m^2 at 7 a.m. and 17 p.m. which is the less amount with respect to the other orientations. Figure (3) shows the sun path diagram for Kharga Oasis through the year for the different direction. The figure shows that the months from march to September need the importance of shading to protect people from solar radiation, also the shading must be from 8 a.m. to 15p.m. The west orientation receives higher intensity than the east orientation due to the albedo effect[39].

2.3. Wind speed and direction

Figure (4) shows the average annual wind direction and speed in Kharga Oasis. It is clear that the wind direction is north to north west with velocity range between 5.4 to 12 m/s in summer season and between 4 to 10 m/s in winter season. This value of wind is enough to use wind mill in this area as one of the renewable energy [39].

3. Different Methods of Evaluating the Thermal Performance of Building Envelope

There are many methods to evaluate the thermal performance of buildings. The first approach is the Bio-climatic method, which has been proposed for buildings that take more passive approach for heating and cooling in areas where acceptable humidity can be maintained. The second method is the experimental methods; there are two types of experimental techniques, which are used to determine the thermal performance and energy efficiency of building under the different external climatic conditions of different seasons.

3.1. Bio-Climatic Method

The thermal comfort of human being is governed by many physiological mechanisms of the body and these vary from person to person. In any particular thermal environment it is difficult to get more than 50% of the people affected to agree that the conditions are comfortable. Personal (activity, clothing, age and sex) and physical environmental variables (air temperature, radiant temperature, relative humidity and air speed) are the principle factors affecting the human thermal comfort. There are many different Bio-climatic methods used to evaluate the thermal performance of building envelope; Mahony tables [(40)], Olgyay chart [(41)], Givoni chart,[(42)], . .etc is simplest methods. These methods are dependent on the external climatic conditions of the location and the approach to thermal comfort. They are not accurate but they give a good idea about design requirements. The Bio-climatic methods are a guide to the various approaches to passive heating and cooling in different climates. They do not give a complete configuration about the thermal performance of the building and its thermal load. On the other hand a formula determined the “indoor Comfort” temperature, T_n relative to an exponentially weighted running average outdoor temperature, T_o and applicable to free running building without mechanically narrowly controlled indoor temperature was developed as follows [(43)].

$$T_n = 17.6 + 0.31*T_o \tag{1}$$

within the limitation that $17.8\ ^oC < T_n < 29.5\ ^oC$.

Where,

T_n = neutrality temperature

T_o = Monthly mean outdoor temperature

Table (1) shows the upper/lower limit temperature ($T_n \pm 2$) of the comfort zone in Kharga Oasis. It is clear from the table that in Kharga Osais the upper limit of comfort in summer season reach to 29.7 and the lower limit of comfort in winter season reach to 19.9; these help individuals to be bear with the high temperature in this region. Givoni’s and ASHREA psychometric charts based on the linear relationship between the temperature amplitude and vapour pressure of the outdoor air in various regions. It can be used at the pre-design analysis stage for assessing the climate, establishing the thermal control task and selecting the appropriate passive control techniques. Figure (5) shows the design strategies on psychometric (according to ASHRE 55-2005) chart with the designed comfort of Kharga Oasis and the extended zone for using ventilation, thermal mass, evaporative cooling, passive heating and mechanical heating and air conditioning . The figure shows that in winter season the climate of Kharga Oasis is near to the comfort zone and using the passive heating system tasks make the building to be in the comfort region. In summer season the figure shows that this region need extensive cooling, and using shading, green area and evaporative cooling help the climate of the building to reach the comfort zone. The figure shows that the mechanical cooling need to reach 780 hours per year (8.9%). Sun shading of windows need to reaches 2437 hours (27.8) %, comfort need to reaches 1924 hours (22 %). Direct evaporative cooling need to reaches

2230 hours (25.5%), passive solar gain reaches to 1227hours (14%) and other needs shown in the figure [39].

Table 1: The upper / lower limit temperature of the comfort zone during the summer season in Kharga Oasis.

Months	Jan	Feb	Mar	Apr	May	Jun.	Jul.	Aug	Sep.	Oct.	Nov	Dec.
Max. Temp.	22.0	27.0	29.6	35.7	39.6	40.2	39.8	38.7	36.5	35.4	28.1	23.8
Min. Temp.	5.2	9.1	12.5	17.9	22.1	24.8	4.7	24.5	23.3	20.5	14.5	7.4
Avg. Temp.	13.9	18.1	21.1	26.8	30.9	32.5	32.3	31.6	29.9	28	21.3	15.6
Tn Temp.	21.9	23.2	24.1	25.9	27.2	27.7	27.6	27.4	26.9	26.3	24.2	22.4
Tuc Temp.	23.9	25.9	26.1	27.9	29.2	29.7	29.6	29.4	28.9	28.3	26.2	24.2
Tlc Temp.	19.9	21.2	22.1	23.9	25.2	25.7	25.6	25.4	24.9	24.3	22.2	20.4

Tn =neutrality (comfort) temperature, Tuc = Upper limit of comfort, Tlc = Lower limit of comfort

3.2. Experimental Technique

There are two types of experimental techniques, which are used to determine the thermal performance and energy efficiency of building under the different external climatic conditions of different seasons. The first one is the temperatures distribution through the envelope elements, indoor air, mean radiant temperatures, and internal surfaces temperatures are measured and recorded for at least three days. Internal and external relative humidity, solar radiation, and wind speed are measured and recorded. Damping factor, decrement factors, and time lag of the building envelope were determined. Also the human degree of sensitivity to the indoor climate is measured and determined by using the indoor weather stations. In which the human degree of sensitivity is given by the Predicted Mean Vote (PMV) value which lies between –3& 3 table (2). It is a set of environmental variables, which satisfies Funger comfort equation [44]. The second one is that used for evaluating energy consumption in the building. It is a technique for measuring the energy consumed, for cooling/heating loads, lighting, equipment's…etc by using voltmeter analysis stations. These measurements are contributing in the field of electrical planning of any countries, and also to know how energy efficiency can be improved. This method of measurement is adequate in the case of commercial building rather than in the case of residential buildings. The third approach is the simulation method, which is carried out by energy software programs.

Table 2: Predicted Mean Vote (PMV) according Funger Equation

Case	**Very cold**	**Cooled**	**Cool**	**Comfort**	**Warm**	**Hot**	**Very hot**
PMV	-3	-2	-1	0	1	2	3

3.3. The Mathematical Model for Thermal Evaluation of Building Envelope

3.3.1. Analytical Study

The thermal response of building is defined as the reaction of the building envelope to some form of heat input (heat gain from external/ internal building envelope, fenestration, and ventilation/ infiltration) and the amount of internal loads (people, light and equipments). It depends mainly on orientation, size, windows to wall ratio, on the thermo physical and optical properties of the building materials, and on the external environmental conditions. All these forms of heat are either sensible or latent heat and transform inside the building to conductive, convective and radiant heat gain which in turn transfer to cooling load. Heat transfer in building takes place by three simultaneous modes; conduction, convection and radiation. Heat is also transfer by ventilation and stored in the building fabric. The general equation governing the heat flow through a homogeneous layer in one dimension is written as; [31].

$$k\,(\partial^2 T / \partial x^2) = \rho\, C_p\,(\partial T / \partial t) \tag{2}$$

Where; T is the temperature (^oC), x is the space dimension (m), t is the time (sec), k is the thermal conductivity (W/m ^oC), ρ is the density (kg/m^3) and C_p is the specific heat; (J/kg ^oC).

The boundary conditions assumed to solve this equation at the outside/inside surfaces are;

$$k\,(\partial T / \partial x)_{x=0} = h_{so}\,(T_{so} - T_{si}) \tag{3}$$

$$k\,(\partial T / \partial x)_{x=l} = h_{si}\,(T_{si} - T_{ai}) \tag{4}$$

Where; T_{so} and T_{si} are the outside / inside surface temperature (^oC), T_{ao} and T_{ai} are the outdoor / indoor air temperature (^oC), h_{so} and h_{si} are the heat transfer coefficient of the outside/inside surface including the radiation and convection components ($W/m^2\ ^oC$). The temperatures and heat flow at both the internal and external surfaces as a resulting solution of Eq. (2) are given as linear equations as follows; (45 & 46)

$$\begin{vmatrix} T\,(o,t) \\ q\,(o,t) \end{vmatrix} = \begin{vmatrix} A & B \\ C & D \end{vmatrix} \begin{vmatrix} T\,(L,t) \\ q\,(L,t) \end{vmatrix} \tag{5}$$

Where;

$A = \mathrm{COSH}\,(1 + i)\,\varphi$ $\qquad B = [\,R / (1 + i)\varphi\,]\ \mathrm{SINH}\,(1 + i)\varphi$

$C = [\,(1 + i)\varphi / R]\ \mathrm{SINH}\,(1 + i)\,\varphi$ $\qquad D = A$

and, R is the thermal resistance of slab; (L/k) ($m^2\ ^oC$ /W)

L is the total thickness of homogeneous layer; (m)

φ is the $(\,\omega\, L^2/ 2\,\alpha\,)^{1/2}$

ω is the frequency of temperature oscillation; $2\pi f$

α is the Thermal diffusivity; $k/ \rho\ C_p$ (m^2/s)

For composite construction of n's layers, and expanding the overall transmission matrix to include the boundary layers of combined convective / radiative resistance, Eq. (2) becomes;

$$\begin{vmatrix} T(o,t) \\ q\,(o,t) \end{vmatrix} = \begin{vmatrix} 1 & R_{so} \\ 0 & 1 \end{vmatrix} \begin{Vmatrix} A_i & B_i \\ C_i & D_i \end{Vmatrix} \begin{vmatrix} 1 & R_{si} \\ 0 & 1 \end{vmatrix} \begin{vmatrix} T\,(L,t) \\ q\,(L,t) \end{vmatrix} \tag{6}$$

Then, the heat fluxes at the innermost and outermost boundaries can be given where; R_{so} /R_{si} are the external/internal surface resistance ($m^2\ ^oC$ /W). The solution of Eqs. (3& 4) due to the heat gain / loss through the building envelopes and the stored in the construction are given as;

$$\alpha_s I = h_{so}\,(T_{so} - T_{ao}) - k\,(\partial T/ \partial x)_{x=o} + q_s \tag{7}$$

$$- k\,(\partial T/ \partial x\,)_{x=l} = h_{si}\,(T_{si} - T_{ai}) + \Sigma\ \ h_r\,(T_{si} - T_i) + q_s \tag{8}$$

Where; α_S is the absorptive of the surface to the shortwave solar radiation (non), I is the total solar radiation affecting the surface (W/m^2), q_s is the storage heat through the structure (W/m^2), and T_i is the other surface temperature (^oC). Also the heat balance equation at the indoor air assuming the casual and internal heat gain equal zero is written as; [47]

$$C_V (T_{ao} - T_{ai}) + \Sigma A_i h_i (T_i - T_{ai}) = o \qquad (9)$$

Where; C_V is ventilation conductance ($W/^oC$), the convective term includes the walls, the ceiling and the floor. The convective and radiation parts of heat transfer; (q_c, q_r) in Watt are calculated in the developed program as follows;

$$q_c = A \; h_c \; (T_i - T_{ai}) \qquad (10)$$

$$q_r = A \; h_r \; (T_{si} - T_i) \qquad (11)$$

Where; A is the surface area (m^2), h_C is the convection heat transfer coefficient ($W/m^2\,^oC$). For internal building surface, h_c= 3 for walls, 4.3 for upward flow to ceiling, and 1.5 for downward flow to floors. For external building surface, h_c= 5.8 + 4.1 v, where v is the wind speed in m/s and h_r is the radiative heat transfer coefficient ($W/m^2\,^oC$) [47].

3.3.2. Numerical Method for Calculation

The admittance procedure is a technique for estimating cooling/heating load and temperature changes under cyclic conditions by using the thermal characteristic (y-value, λ ,φ , Sf) of the building structure. It is dependent on determining the daily mean value and the swing about this mean. A computer program using this method to calculate the heating / cooling load and the environmental air temperature were calculated. The "sol-air temperature"; T_{eo} is written in a mathematical form as follow [48].

$$T_{eo,t} = T_{ao,t} + R_{so} \, (\alpha_s \; I_t - \; \varepsilon \Delta R) \qquad (12)$$

The actual rate of heat transfer into the room at any time t (Q_t)is given as the sum of both the mean and swing value about the mean, and can be written in a final form [46]

$$Q_t = A \, U \; \{(T_{eo} - T_{ei}) + \lambda \, (T_{eo,t-\varphi} - T_{eo})\} \qquad (13)$$

Where; T_{ei} is the constant indoor environmental temperature (^oC), and U is the heat transfer coefficient. Heat transferred through partition, ceiling and floor between the conditioned space and the adjacent space due to the temperature difference between them is given as ;

$$Q_{ad,t} = AU \, (T_{ad,t} - T_{ei}) \qquad (14)$$

Where; T_{ad} is the adjacent space temperature at time t (^oC).

The total instantaneous rate of heat gain through a glazing material (TIHG) is balanced by conduction heat gain/loss due to air temperature difference between outdoor and indoor, and the solar heat gain due to transmitted and absorbed solar energy [48].

$$TIHG_t = U_g \, (T_{ao,\,t} - T_{ei}) + (\tau + \alpha \, U_g / \, h_o) \, I \qquad (15)$$

Where; U_g is the coefficient of heat flow of the glass ($1/ (R_{so} + R_{si})$); ($W/m^2\,^oC$).

The term ($\tau + \alpha \; U_g / \; h_o$) is called the "Solar Heat Gain Coefficient". For reference glazing material for the ASHRAE procedure (DSA), it is equal 0.87 [48] According to Loudon, [33]. ($\tau + \alpha \; U_g / \; h_o$) is called the "Solar Gain Factor". This instantaneous heat gain value is converted to cooling load after made a modification for the cyclic transmitted part by means of the surface factor (46). The admittance method gives the environmental temperature where, it is a convenient temperature of calculating rates of heat flow for both the steady state and diurnal temperature swings. . It need the magnitudes of the various load fluctuations at each point in time for each harmonic considered and about the mean condition are determined and modified by the decrement and surface factors appropriate to their type and frequency. This gives the energy fluctuation imposed on the enclosure at each frequency and experienced at some time after the initial excitation, a delay which depends on the time lag related to the factor used. The total fluctuating load at each point in time and at each frequency is obtained by summing the individual load fluctuation released at each time. In final form it is given as;

$$T_{ei,t} = T_{ei}\,(\text{mean}) + T_{ei,t}\,(\text{swing}) \qquad (16)$$

Where; T_{ei} (mean) / $T_{ei,t}$ (swing) is the mean / swing internal environmental temperature; (^{o}C), they were developed from the daily mean and swing in the energy gain.

The mean total energy gain from walls, roof, windows, people, and lighting (with neglecting here the presence of people and lighting) is given as;

$$Q_{tm} = \{\Sigma(AU)_{si} + \Sigma\,(AU)_{gj} + C_v)\,(T_{ei} - T_{ao}) \qquad (17)$$

Where; Σ(AU) is the sum product of exposed surface / glass areas and the appropriate U-value; (W/ ^{o}C).

$$C_v = 0.33\ N\ V \qquad \text{(low rate of ventilation),}$$

$$1/C_v = 1/0.33\ NV + 1/4.8\ \Sigma\ A \qquad \text{(higher rate of ventilation),}$$

N is the rate of air interchange; (h^{-1}), V is the room volume; (m^3), and ΣA is the total areas of surfaces bounding the enclosure, weather internal or external. The swing total energy gain from walls, roof, windows, ventilation, people, and lighting given as;

$$Q_{ts} = (\ \Sigma A_j\ Y_j + C_{v,t})\ T_{ei,t} \qquad (18)$$

Where; $\Sigma A_j Y_j$ is the area-weighted admittance of room; (W/ ^{o}C), it is equal to the sum of product of areas (solid and glass weather external or internal) and the appropriate Y-value of each surface. Table (3) summarized the equation for heating and cooling.

3.3.3. Algorithms of the Computer Program

A computer program is developed and prepared in order to simulate and analyses the dynamic building thermal behavior using the Basic language. The heat transfer problem under dynamic conditions is solved by means of the admittance method. This program is developed to calculate the heating and cooling load of a residential building in Egypt and also to predict the environmental temperature in three step;

- Firstly, calculate the hourly heat gains deriving by each building component (walls, windows, doors, etc.)under the hypothesis that the environmental temperature is constant.
- Secondly, calculate the heating and cooling load of a building where, the room heat

Table 3: Summarized the equation for heating and cooling loads

Load Source	Equation	Description
External Roof or Walls	$\bar{Q}_{cond} = U * A * (\bar{T}_{eo} - T_{ei})$ $\tilde{Q}_{cond} = U*A*DF*(T_{eo}(\theta-\phi) - \bar{T}_{eo})$	The cooling / heating load composed of two parts the mean part ($\bar{Q}_{cond}$) and the swing part about the mean ($\tilde{Q}_{cond}$) ► Environmental indoor air temp. ► Mean sol - air temp. ► Sol - air temp. at time $(\theta-\phi)$ ► Decrement factor ► Surface area ► Design heat transfer coefficients These two parts depend on inside and outside design dry bulb temps., the colour of external surface, the latitude, orientation, time of calculation and the thermophysical properties of the construction.
Partiton, Ceiling & Floor	$Q_{part} = U * A * \Delta T$	► Design heat transfer coefficient. ► Surface area. ► Design temperature difference.
Glass Conduction	$Q_{gcond} = U_g * A_g * \Delta T$	► Design heat transfer coefficient according to the glass type & internal / externel shading. ► Net glass area. ► Design temperature difference
Glass Solar	$\bar{QS}_{gm} = S * A_g * \bar{I}_m$ $\tilde{QS}_{gs} = S_a * A_g * (I(\theta) - \bar{I}_m)$	► Solar gain factor ► Mean solor intensity. ► Mean glass load. ► Swing of solar intensity about daily mean. ► Alternating solar gain Factor. ► Swing glass load
Internal Light	$\bar{q}_{Lt} = No.*LHG*A_f*DRT/24$ $\tilde{q}_{Lt} = No.*LHG(\theta)*A_f - \bar{q}_{Lt}$ $Q_{Lt\ tot}(t)$	► Light number. ► Heat gain of each lamp ► Floor area ► Duration time of lighting. ► Mean light heat gian ► Swing light heat gain ► The total load fron light
People	$\bar{q}_{occ} = No. * PHG * DRT/24$ $\tilde{q}_{occ} = PHG(t) - \bar{q}_{occ}$ $Q_{occ}(t)$	► Number of occupants in space. ► Heat gain from occupants. Mean occupants heat gain. ► Swing occupants heat gain ► Total load from occupants.
Ventilation and Infilraion	$q_{sen} = 1.232 * ACH * \Delta T$ $q_{lat} = 3012 * ACH * \Delta W$ $Q_{tot} = 4.334 * ACH * \Delta h$	Sensible heat gain ► Design temp. diff. Laten heat gain ► Humidity ratio diff Total heat gain, $(q_{tot}) = (q_{sen} + q_{lat})$ ► Enthalpy diff. ► Air change per hour ► Constant according to each part This heat gain depend on the ACH and the inside and outsid dry bulb temp. and on the humidity ratio.

load is the heat quantity that has to be given or subtracted from the room in order to maintain the air temperature equal to a constant value.

- The third, by means of the energy balance of the room is rebuilt in order to calculate the actual internal air temperature.

A master program is prepared. Through it, the hourly cooling/heating load due to each source (walls, windows, doors, infiltration/ventilation, occupants and light) is calculated, and the environmental temperature is estimated. This program included within it four subroutine. The first one to calculate the outdoor air temperature using the maximum and diurnal range temperature of the given site with the percentage value [48]. The second subroutine program is developed to calculate the direct, diffuse and global solar radiation intensity on horizontal surface and obtained in hourly values. The input data file for this subroutine includes; the day, month, latitude, the cloud cover, and the annual relative humidity. Figure (6) shows a flow chart subroutine of solar radiation intensity (Solar subroutine) on horizontal surface. These input data can be taken from a file called the weather data file. The third subroutine program is concerned with the characteristics of the construction of the walls such as the conductance (U-value), the admittance (Y-value), the decrement factor (λ), time lag (φ) and the surface factor (Sf). The input data file for this subroutine includes the inside / outside surface resistance (R_{si} & R_{so}), the air gap resistance (R_{ag}), and the thermo-physical properties of the layers of the construction (thermal conductivity, k, density; ρ, and specific heat; C_p) and their thicknesses. Figure (7) shows a flow chart of thermo-physical and characteristics properties subroutine (Admit subroutine). These input data taken from a file called the construction data file. This data file contains 5 different walls in which each wall can be composed of 5 layers (may contain air gap in between). The fourth subroutine program is developed to simulate the direct and diffuse solar intensity on vertical surfaces according to their orientations. It is also concerned with the heat gain due to transmission and absorption for both the direct and diffuse solar intensity through the window (shaded or un-shaded). Figure (8) shows a flow chart subroutine of solar radiation intensity on vertical (Opaque/ window) surfaces area. To simulate the master program a building data file is developed to include the geometry of the building, its volume, inside constant environmental temperature and humidity ratio at which the calculation done, the number of walls, its absorpetivity, whether it is external or internal, its length and width, and the azimuth of each wall. Also the temperature of the neighbor zone (whether it is equal to the outdoor air or constant value or has different temperature) for this wall. Also shows if this wall has windows, door or hasn't any opening. For each window the characteristics of it (U-value and y- value) and its dimensions and whether this window shaded or not. If the window shaded, the data include the width of the shade device and the distance between it and the window. For each door the area and U-value are found. The output data of this program starting with the city name and its altitude, the day and month of calculation, the hourly values of the weather data, the mean environmental conditions, the characteristic of each construction (U-value, Y-value, λ , φ ,Sf), its area and its wall azimuth angle, the average values of the cooling/heating load of each component and also the total of the zone and the hourly values of the heating and cooling load of each component and the indoor environmental temperature. These output values printed or stored in a file.

The program has been applied to a prefabricated apartment in the new city of 15 May of Egypt. A validation of the program including a comparison between the measured and estimated indoor air temperature as shown in Figure (9)[4].

4. Case Study

To study the thermal performance of building in Kharga Oasis, a test model of 10*10*3 m is chosen and oriented to north direction. The simulation is carried out on the building by using different alternative walls and roofs to reach to the favorite building materials used in this region. Tables (4& 5) describe the thermo-physical properties and thermo-physical characteristics of these walls and roof used. In this study July 21 was chosen for the cooling load calculation as an indication for the hottest period and Jun. 21 was chosen for the heating load calculation as an indication for the coldest period.

Table 4: Walls description of different building materials with / without thermal insulation and their thermo-physical properties and characteristics

No	Wall Description	Thermo-physical Properties				Thermo-physical characteristics				
		L	k	D	Cp	U	R	TL	DF	Y
		m	W/m°C	Kg/m^3	J/Kg°C	W/m^2°C	m^2°C/W		non	W/m^2°C
1	Inside plaster*	0.025	0.727	1602	840	2.351	0.425	8	.33	4.993
	Cement brick	0.25	1.4	2000	880					
	Outside plaster*	0.025	1.4	2000	880					
2	Heavy sand brick	0.25	1.4	2000	880	2.475	0.404	7	.4	4.965
3	Sand stone	0.25	0.97	2260	840	1.982	0.505	9.4	.26	4.829
4	Lim stone	0.25	0.73	2380	840	1.697	0.589	10.8	.21	4.699
5	Clay brick	0.25	0.42	1470	840	1.188	0.842	10.6	.27	4.14
6	Light sand brick	0.25	0.29	483	850	0.902	1.109	9.3	.38	3.666
7	Cement brick	0.25	1.4	2000	880	0.877	1.14	10.8	.17	5.32
	Polystyrean layer	0.025	0.035	16	1400					
	Cement brick	0.25	1.4	2000	880					
8	Cement brick	0.25	1.4	2000	880	0.539	1.855	11.1	.15	5.369
	Polystyrean layer	0.05	0.035	16	1400					
	Cement brick	0.25	1.4	2000	880					
9	Cement brick	0.25	1.4	2000	880	0.389	2.571	11.3	.14	5.386
	Polystyrean layer	0.075	0.035	16	1400					
	Cement brick	0.25	1.4	2000	880					
10	Cement brick	0.25	1.4	2000	880	0.305	3.279	11.5	.14	5.394
	Polystyrean layer	0.1	0.035	16	1400					
	Cement brick	0.25	1.4	2000	880					

Rso = 0.055 Rsi = 0.123

* for each wall material inside / outside plaster layer with its properties were repeated

5. RESULTS AND DISCUSSION

5.1 The thermal response of walls

The quantitative effect of building envelop (walls/ roof) depend on their thicknesses and thermo-physical properties, i.e the type of the materials affect the temperature of both the indoor air and surfaces and thus have a very pronounced effect on the occupants' comfort in natural conditions. While in air conditioned space, the thermo-physical properties of the materials used determined the amount of heating /cooling load which is provided and also the temperature of the internal surfaces. To investigate the effect of building materials on heating /cooling load of building in Kharga Oasis, different building materials of different masses and U-value are used in the wall construction of the case study. Each wall composed of 0.25 m brick/ stone and 0.025m internal/ external plaster. Table (4) illustrates the building materials used with their thermo-physical properties and characteristics. The roof of this case is commen reinforced concrete of 0.1m and the absorpetivity of the wall is chosen as light color with value equal 0.3. Figure (10) illustrate the hourly variation of the cooling load of south wall with different building materials summer season. The figure also shows the outdoor air temperature which reach it's maximum value of about 40° C and it's minimum value of about 24°C with a diurnal range of about 15°C and still over 30°C for 12 hours. The figure demonstrate that walls have U-value approximately ≥ 2 W/m^2°C (cement brick, sand brick and sand stone) give a higher and large fluctuation of cooling load. The figure also shows that walls have U-value < 2 W/m^2°C (clay brick, light brick and lime stone) have a nearly steady fluctuation and approximately equal load. Minimum load found between 9.0 am and 13.0 pm, while the maximum load found between 20.0 pm and 24.0 mind night with different time lag

Table 5: Roof description with different construction type / different insulation thickness And their thermo-physical Properties and thermo-physical characteristics

No	Roof Description	Thermo-physical Properties				Thermo-physical characteristics				
		L	k	D	Cp	U	R	TL	DF	Y
		m	W/m°C	Kg/m³	J/Kg°C	W/m²°C	m²°C/W		non	W/m²°C
1	Inside plaster*	0.025	0.727	1602	840					
	Heavy concrete layer	0.15	1.4	2700	900	2.043	0.489	9	.25	5.221
	Sand layer*	0.05	0.39	1598	880					
	Cement tiles and mortar*	0.05	1.2	2200	1000					
2	Lika concrete layer	0.15	0.28	1290	1000	1.089	0.918	11	.27	3.944
3	Normal concrete layer	0.15	1.4	2700	900	2.043	Shaded	9	.25	5.221
4	Heavy concrete layer	0.10	1.4	2700	900	2.204	0.454	7.7	.36	5.269
5	Heavy concrete layer	0.1	1.4	2700	900					
	Polystyrean layer	0.05	0.025	16	1400	0.531	1.883	10.1	.21	5.526
6	Heavy concrete layer	0.10	1.4	2700	900					
	Polystyrean layer	0.075	0.025	16	1400	0.385	2.597	10.3	.20	5.54
7	Heavy concrete layer	0.10	1.4	2700	900					
	Polystyrean layer	0.1	0.025	16	1400	0.302	3.311	10.5	.19	5.547
8	Heavy concrete layer	0.10	1.4	2700	900					
	Polystyrean layer	0.125	0.025	16	1400	0.248	4.032	10.7	.19	5.551
9	Heavy concrete layer	0.10	1.4	2700	900					
	Polystyrean layer	0.15	0.025	16	1400	0.211	4.739	10.9	.19	5.554

Rso = 0.055 Rsi = 0.123

For each roof inside plaster, Sand layer, cement tiles and mortar were repeated.

between them according to their heat capacity. Table (6) illustrate the total cooling / heating load of 9 different walls construction versis the U-value under the external climatic conditions of summer/ winter seasons in Kharga Oasis. The figure shows that as the U-value increase the cooling/ heating load increase. Walls with U-value approximately ≥ 2 W/m²°C give the higher load. Related to table (4) the U-value varies between 0.902 and 2,475 W/m²°C, with a thermal resistance varies between 0.425 and 1.109 m²°C/W. while the Egyptian energy code require R-value varies between 0.8 and 1.3 m²°C/W for desert region from Egypt.

Table 6: The wall construction with their U-value, R-value, and the total cooling / heating load .

Walls Construction									
U-value (W/m²°C)	0.902	0.926	1.188	1.246	1.697	1.906	1.982	2.351	2.475
R-Value (m²°C/W)	1.109	1.08	0.842	0.803	0.589	0.525	0.505	0.425	0.404
Cooling load (KW)	24.6	25.3	32.4	34.0	46.3	52.0	54.1	64.1	67.5
Heating load (KW)	-18.1	-18.6	-23.9	-25.1	-34.1	-38.3	-39.8	-47.2	-49.7

Figure (11) illustrate the hourly variation of the cooling load of the different wall orientation for the building case study during summer season under the external climatic condition of Kharga Oasis. In this case clay brick of 0.25 m with 0.025 m inside / outside plaster layer was used. The roof of this case is common reinforced concrete of 0.1m. the apsorbetivity of the wall is chosen as medium color with value equal 0.6. The figure demonstrate that all the walls of different directions have the same thermal behavior between 7 a.m. and 15 p.m. and by difference in their values .Due to the difference of the amount of solar radiation fallen on each the maximum cooling load of east/ west directions accrue at 20 p.m. hour and 3a.m. hour the west cooling load is high than the east wall by about 17.7% due to the exposed of the west direction to the high ambient temperature of the after noon and the albido phenomena. The north cooling load is near to the south cooling load and increases about it in the early morning and late afternoon by about 3.4%. It is also clear from the figure that the east / west direction are higher than the north/ south direction. Finally it is clear from the figure the importance of using north/ south direction as favor faces for the building and the importance of reducing the cooling load of both east and west direction. From figure (10) and table (6) it is clear that the required R- Value of walls can be achieved by using traditional building materials with different thickness but using thermal insulation can verify the R-Value required without increase the wall thickness. Figure (12) shows the hourly variation of the cooling load of west wall with and without thermal insulation. In this case cement brick of 0.25 m with 0.025 m inside / outside plaster layer was used. The roof of this case is common reinforced concrete of 0.1m. The apsorbetivity of the wall is chosen as medium color with value equal 0.6. The figure shows the effect of thermal insulation in reducing the cooling load, and the effect of increasing the insulation thickness in reducing the cooling load. Figure (12) shows the high fluctuation of wall without insulation with respect to the approximately nearly stable of the wall with insulation of different thickness. The figure also shows that minimum insulation thickness valid a reduction in the cooling load to about 63%. Table (7) shows the total walls cooling load and the reduction per cent in cooling load of all walls when using the thermal insulation of different thicknesses.

Table 7: The total walls cooling load and the reduction per cent in cooling load R-Value of all walls when using the thermal insulation of different thicknesses.

Walls with Different Insulation Thickness					
Thicness (cm)	0	2.5	5.0	7.5	10.0
R-Value (m^2K/W)	0.425	1.14	1.855	2.571	3.279
Cooling load (W)	78856	29432	18092	13060	10218
Reduction (%)	0	63	77	83	87

This table illustrate that for wall with low thermal resistance in Kharga Oasis in Egypt thermal insulation material must used in all exposed walls to save thermal comfort inside building spaces during long summer season, and conserve energy. Also it is clear that thermal insulation of thickness between 0.03 and 0.05cm is enough to valid the thermal resistance according to the Egyptian Energy Code.

5.2 The thermal response of Roof

The external surface of the roof is often subjected to the largest temperature fluctuations, and the high intensity of solar radiation. So in hot countries it is believed that the roof is the main heating element of a building in summer. Simulation were carried out on the case study regarding the walls is clay brick of 0.25 m and with 0.025 m inside/ outside plaster layer was used. Different roof constructions were used and the apsorbetivity of the wall and roof is chosen as medium color with value equal 0.6. Figure (13) illustrate the hourly variation of the outdoor air temperature and the cooling load of roof constructed from different building materials during summer season. The figure shows that all the roof have the same behavior with different in the maximum and minimum cooling load values and shifting in the peak time. The figure shows that roof of U-value approximately grater than 1.5 $W/m^{2o}C$ (Heavy concrete, light concrete, Roof with sand layer and roof with air gap) give the higher and large fluctuation load through the day . The difference in the load values of these roofs during the afternoon period is clear where the peak value of roof with air gap /sand layer are less than the heavy concrete by about 25%, and 16% , while these difference are not clear through the night time and early hours of the day. Roof with U-value less than 1.5 $W/m^{2o}C$ give low load than the other roofs through the day. These roofs give nearly load through the night and early hours of the day while in the after noon they behave approximately the same with one hour late. The figure also shows that roof with minimum U-value and maximum R-Value give the minimum load with maximum time lag. From these results we can notes that air gap layer or sand layer may be used to minimize the cooling load of heavy concrete roof. Table (8) shows the roof construction with their U-value, R-value, the maximum and the total cooling load.

Table 8: The roof construction with their U-value, R-value,
the maximum and the total cooling load .

U-value (W/m^2K)	Roof Construction						
	Heavy concrete	Light concrete	Sand Layer	Air gap	Clay Roof	Lika roof	Shaded Roof
	2.043	1.879	1.719	1.652	1.352	1.089	2.043
R-Value (m^2K/W)	0.489	0.532	0.582	0.605	0.74	0.918	0.489
Max. Load (W)	4634	4316	3910	3488	3355	2526	1221
Cooling load (W)	75258	69199	63296	60830	49813	40123	18806

From figure (13) and table (8) it is clear that the required R- Value of residential building according to the Egyptian Energy Code in Kharga Oasis (3 $m^{2o}C/W$) is not valid. Different insulation materials (Vermiculite, pearlite, sand, and polystyrene layer) added to the concrete roof can increase the thermal resistance of the roof. Figure (14) shows the hourly variation of the cooling load of roof with and without polystyrene layer. The figure shows the effect of thermal insulation in reducing the cooling load, and the effect of increasing the insulation thickness in reducing the cooling load. Table (9) shows the total roof cooling load with / without polystyrene layer, and the reduction per cent in cooling load as thermal insulation with different thickness used. The figure shows the reduction in cooling load increase as the insulation layer thickness increase. Roof with thermal insulation layer of different thickness give loads approximately the same and far away from the roof without insulation

Table 9: The total roof cooling load and the reduction per cent in cooling load
when using the thermal insulation of different thicknesses.

Roofs with different Insulation Thickness						
Thickness (cm)	0	5	7.5	10	12.5	15
R-Value (m^2K/W)	0.454	1.883	2.597	3.311	4.032	4.739
Cooling load (W)	81183	19567	14185	11124	9150	7771
Reduction (%)	0	76	82.5	86	89	90

5.3 The Thermal Response of Windows on the Cooling Load

to clarify the effect of window ratio on the cooling load of residential building in Kharga Oasis, we simulate the case study with window of differ ratio start from 0 % to 100% of the south direction. Figure (15) shows the cooling load of south wall and window with different glass to wall ratio due to the solar heat gain and conduction. The figure shows that the total cooling load of the south wall without any opening reach to 7200 W. the figure illustrate that as the window ratio increasers the cooling load from the solar heat gain and due to conduction through the window are increased rapidly. The total cooling load of the south wall is approximately equal to the cooling load from solar heat gain of window with ratio of 20%. This figure shows that how much the glass is week to gain heat by conduction and solar. From the figure we conclude that in hot region like Kharga Oasis; it is perfable to make the opening very small, but smart glass can be used for large opening in this area without increasing the load on the building.

6. CONCLUSIONS

The results of this study show that energy efficiency of building envelope system is generally expensive and are cost-effective especially for residential buildings. The results of this study concluded that.

1. Bio-climatic methods are important to verify the first idea of design for non-conditioning buildings. Analysis by Mahoney tables investigates that, the planning of city must be compact and the opening must be less than 20%. The walls and roof must have high heat storage and building design must be compact.
2. Digital computer solutions for the problems of periodic heat flow through building sections play a major role in enhancing energy code for residential buildings.
3. Simulation methods and the parametric analysis are required in helping engineer and physics' to evaluate the energy consumption of the buildings and the environmental air temperature before constructed.
4. The advantages of the matrix method over other exact mathematical methods, in solving the Fourier heat conduction equation, especially in the case of multi-layered sections, have been will established.
5. The matrix method is one of the calculation techniques which give realistic answers to the problem of cyclic temperature predictions in buildings.
6. The main advantage of the admittance procedure is that acceptable temperature and energy predictions are given by a reasonable digital computer solution.
7. The three parameters Y, λ, Sf give designers a qualitative indication of the likely behavior of buildings.
8. The thermo-physical properties and characteristics of most common building materials in Egypt are listed in tables
9. Tradition building material with thermal resistance R-value varies between 0.8 and 1.3 - $m^{2o}C/W$ is suitable for exposed walls in Kharga Oasis (desert region) according to the Egyptian Residential Buildings Energy Code, ECP 306-2005
10. For exposed roofs in Kharga Oasis and the required thermal resistance has a minimum R-value =3 m K/W.
11. To verify Egyptian Residential Buildings Energy Code, ECP 306-2005, the Thermal insulation thicknesses between 0.03-0.05m for exposed walls and 0.05m for exposed roofs are suitable to valid the required thermal resistance in Kharga Oasis
12. Light color and shading help in decrease the direct share of solar radiation on heat gain through walls.

13. For non-conditioned building orientation, shape, size, shading devices and control opening areas in the envelope has the first priority.
14. Bio-climatic by ASHREA chart indicate that the mechanical cooling need reach to 9.0 %per year, Sun shading of windows 27.8 %, Direct evaporative cooling 25.5.
15. New smart building materials can be used to improve the thermal performance of the building and save energy of commercial and government buildings in Kharga.
16. Smart glass with good optical properties can be used to improve the thermal performance of the building and save energy of commercial and government buildings in Kharga and enable architecture to made opining with large area.
17. In summer season where the average outdoor temperature is up to 30 ^{o}C, the traditional building is high sensitive to external climatic conditions. In this case some additional passive or low energy cooling system, air catcher, court and evaporative cooling, is needed to ensure indoor comfort.
18. According to the low relative humidity of the region, evaporative cooling considered a good passive system to improve the indoor air climate.
19. Although people living in hot regions are acclimatization to the prevailing thermal environment , they prefer higher temperature and would suffer less in hot environment. And the upper limit of comfort reach to 30^{o}C
20 Wind velocity range between 5.4 to 12 m/s in summer season and between 4 to 10 m/s in winter season is enough to use wind mail in this area. Also solar water collector must be used in this area as types of the renewable energy needed

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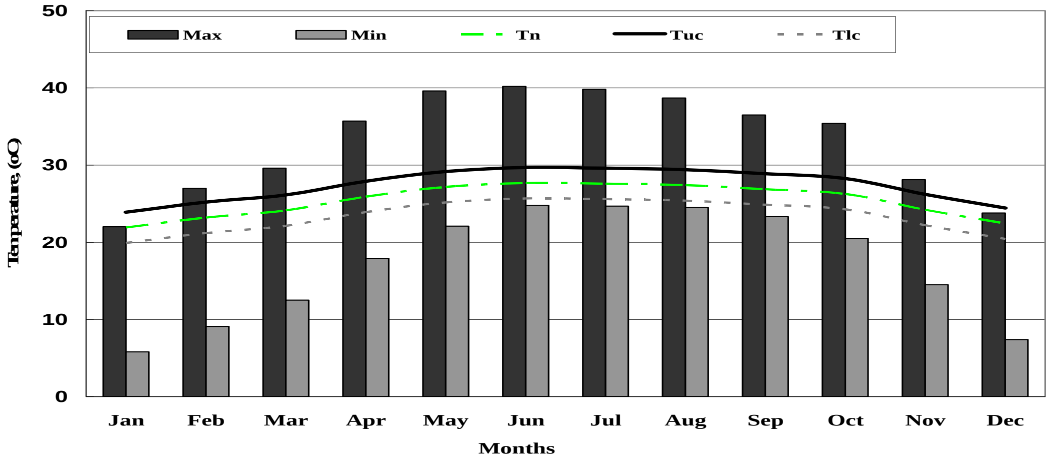


Fig. 1a. The monthly mean maximum / minimum of the outdoor air temperature, the neutrality temperature and the upper/lower limit temperature of comfort in Kharga Oasis.

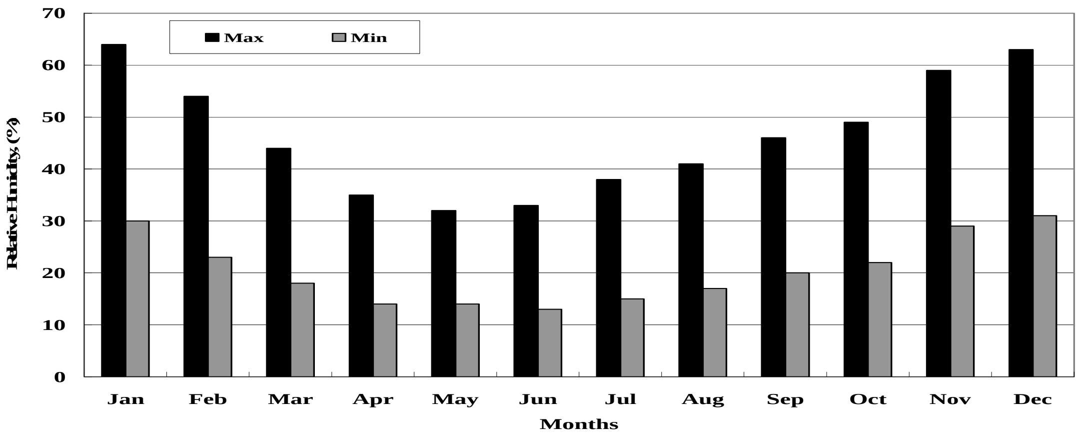


Fig. 1b. The monthly mean maximum / minimum relative humidity in kharga Oasis.

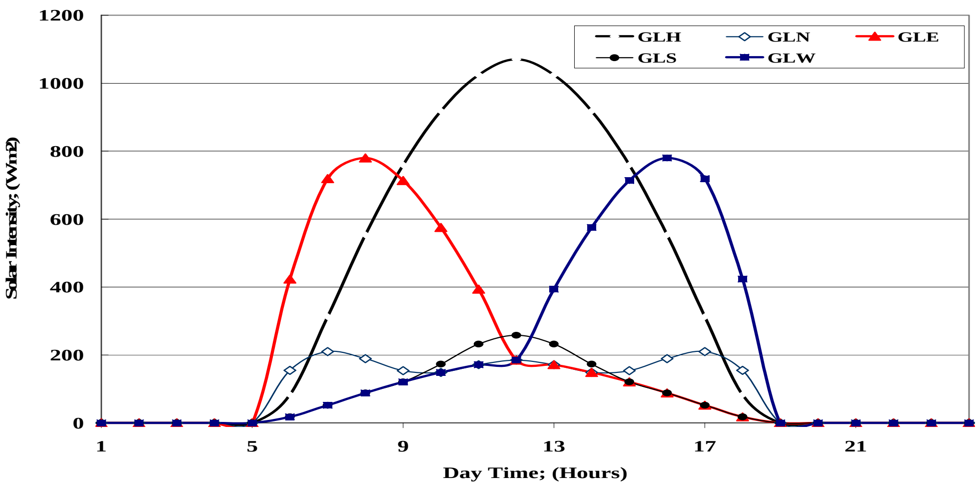


Fig. 2. The variation of the computed solar intensity on the horizontal surface and walls of different orientations on Kharga Oasis, during summer season (July, 21).

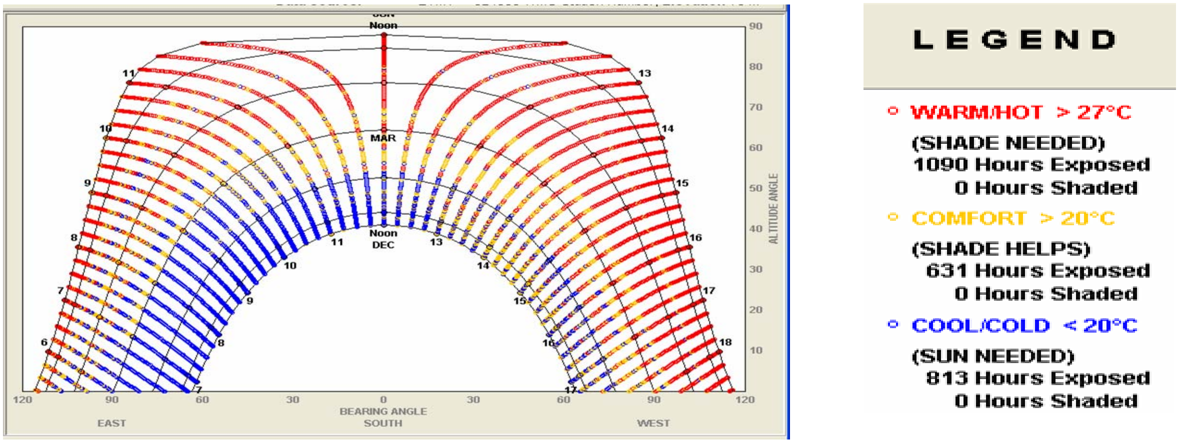


Fig. 3.The sun path diagram for Kharga Oasis through the year for the different direction.

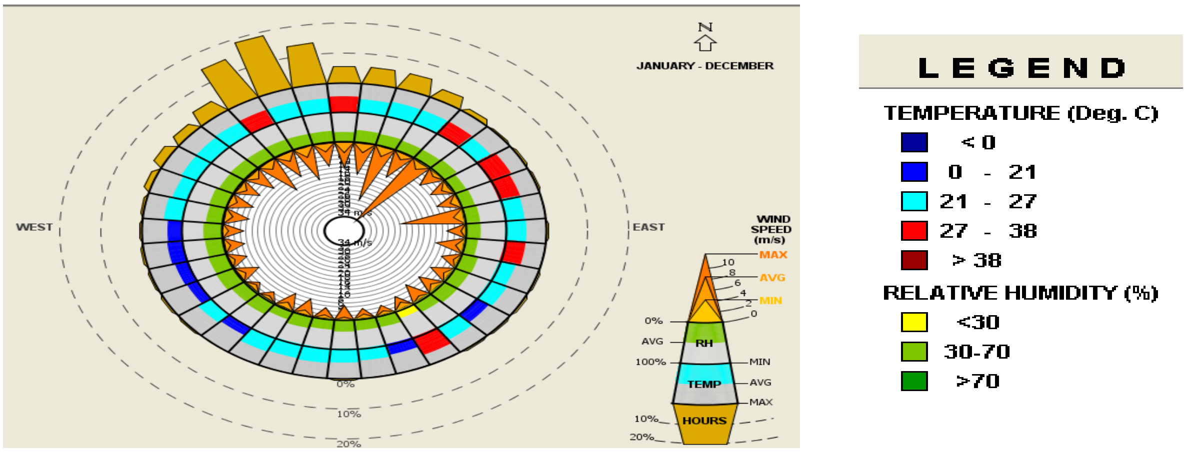


Fig. 4. The average annual wind direction and speed in Kharga Oasis.

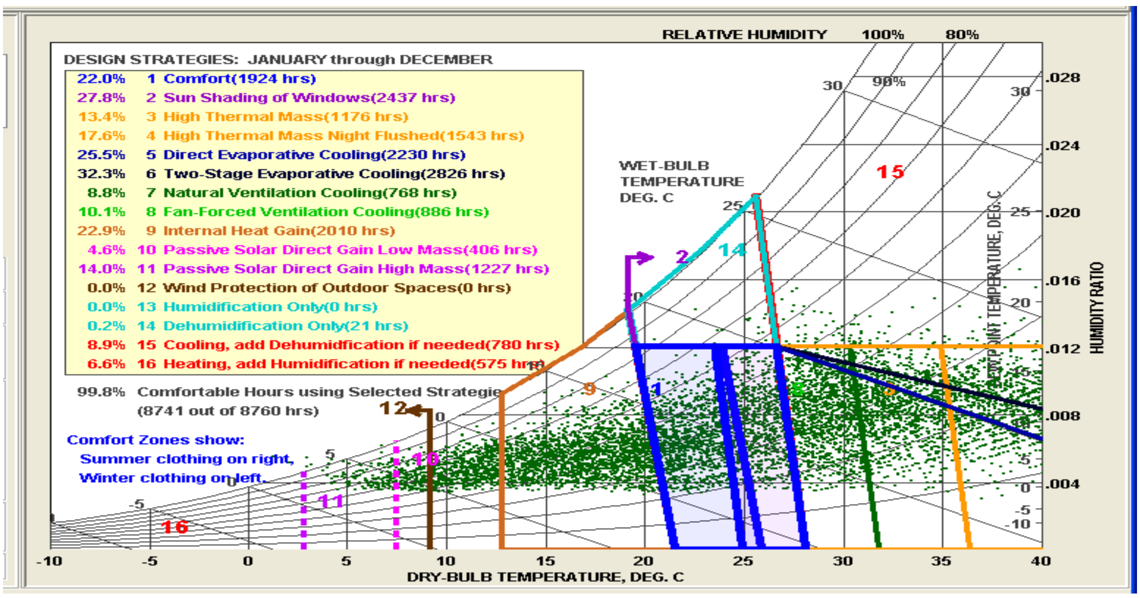


Fig.5. The design strategies on psychometric chart (according to ASHRE 55-2005) with the designed comfort of Kharga Oasis and the extended zone.

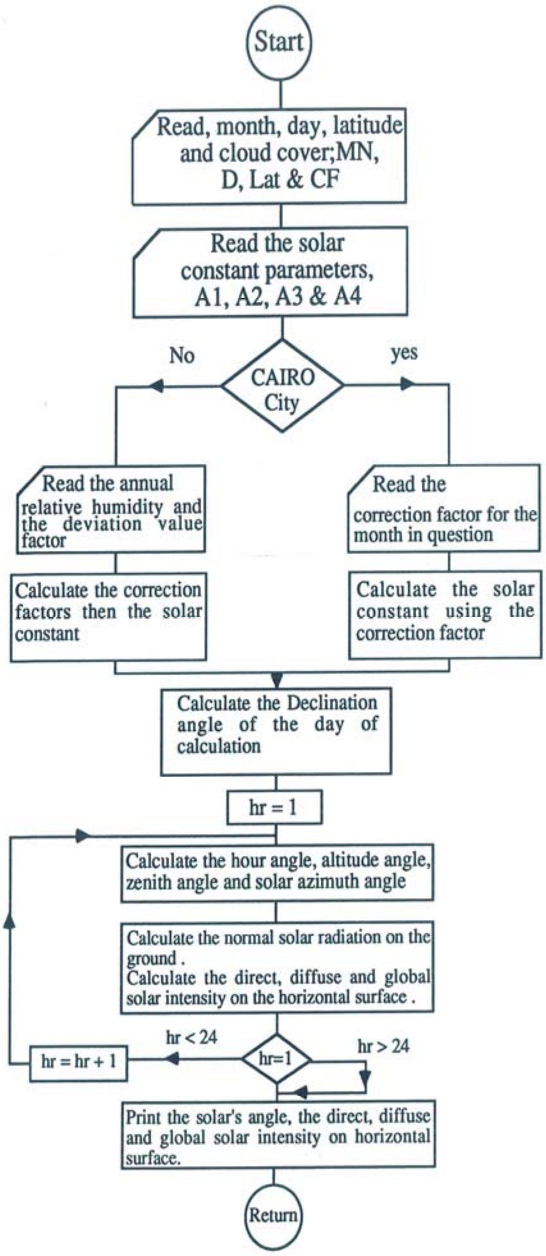


Fig. 6. Flow chart of solar radiation intensity subroutine on horizontal surface (SOLAR Subroutine.

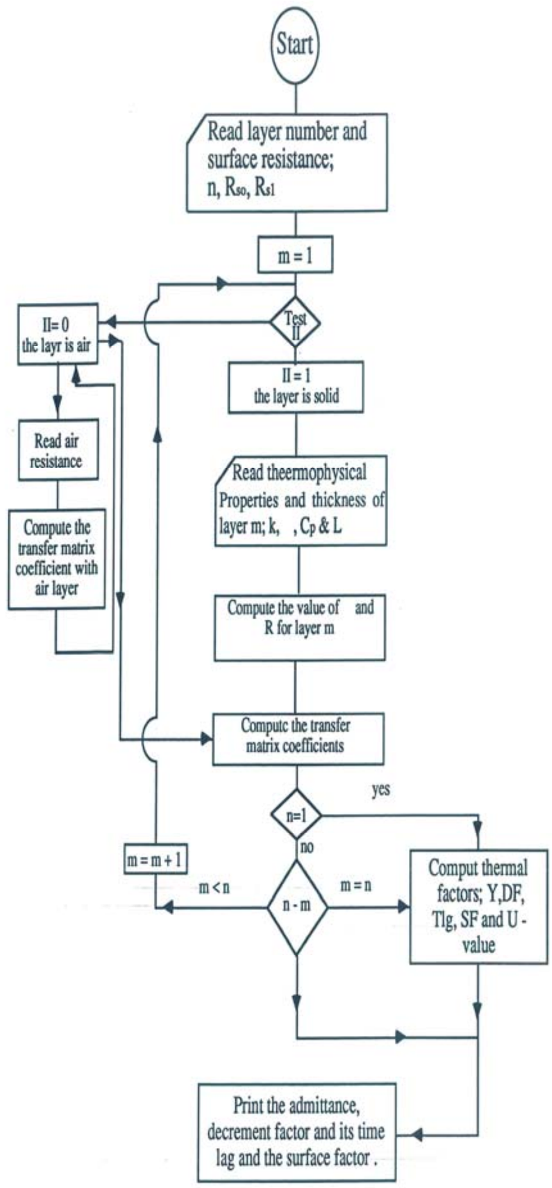


Fig. 7. Flow chart of thermo-physical and characteristics properties subroutine (ADMIT Subroutine).

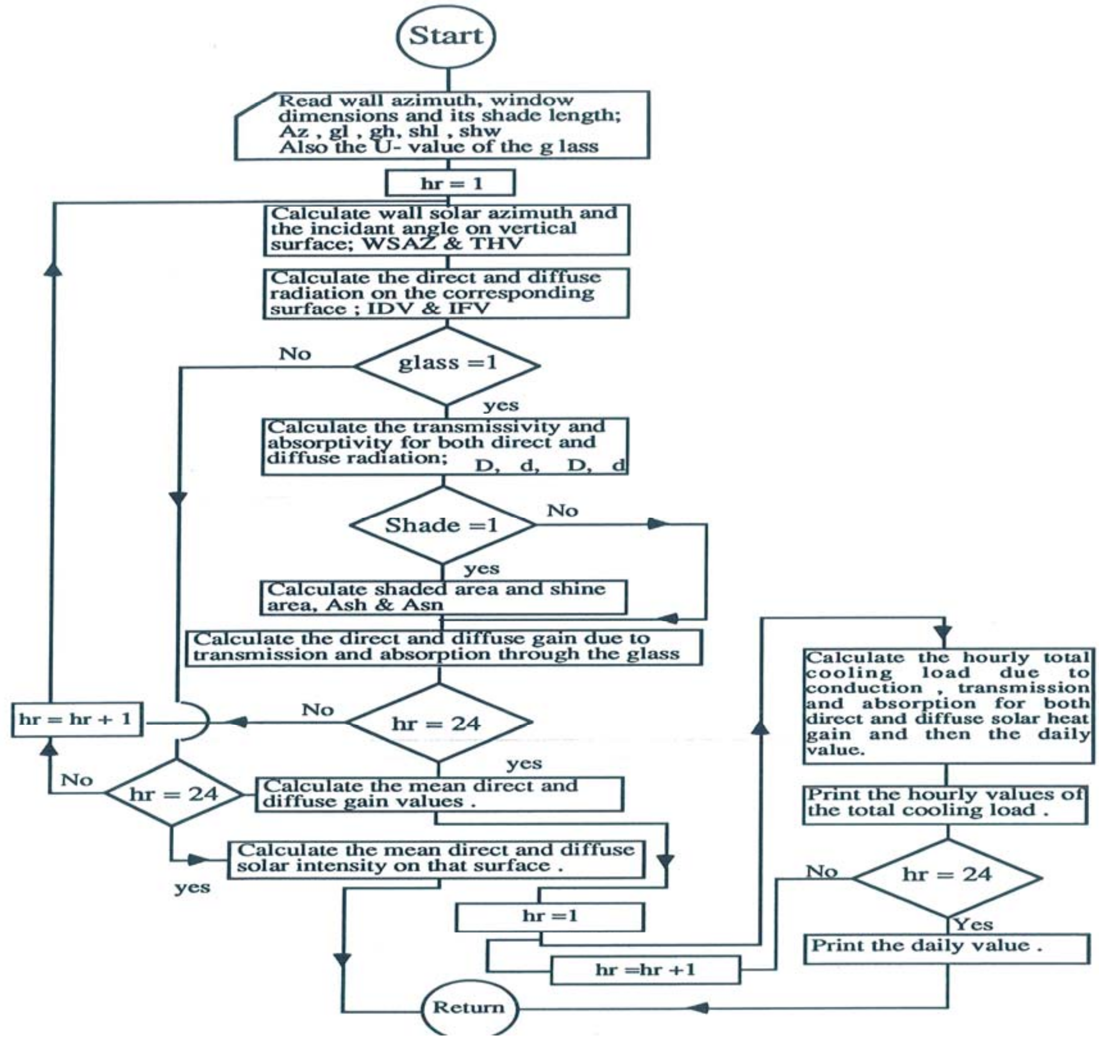


Fig. 8. Flow chart of solar radiation intensity subroutine on horizontal surface.

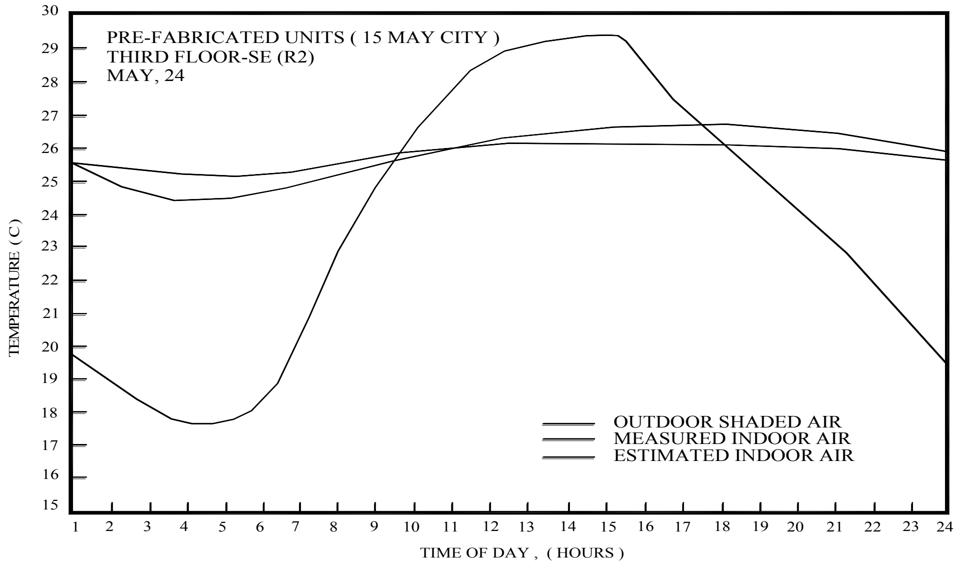


Fig. 9. Comparison between measured and estimated indoor air temperature of rooms 2 in the 3rd floor of pre-fabricated concrete building in 15-May city during summer season.

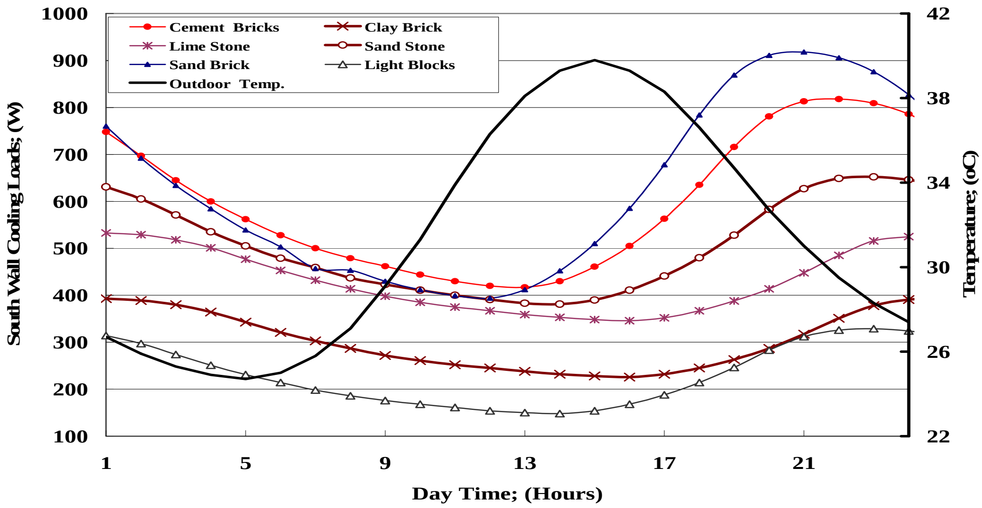


Fig. 10. The hourly variation of south wall cooling load for different building materials.

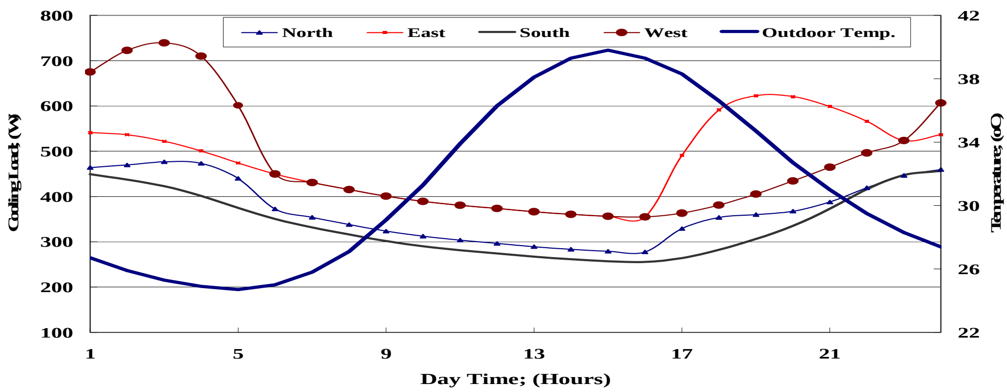


Fig. 11. The hourly variation of the cooling load of different orientation

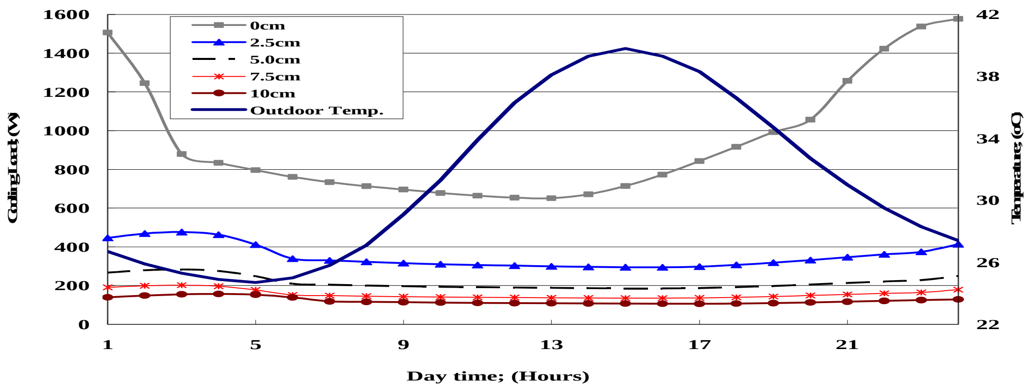


Fig. 12. The hourly variation of the cooling load of west wall with and without thermal insulation.

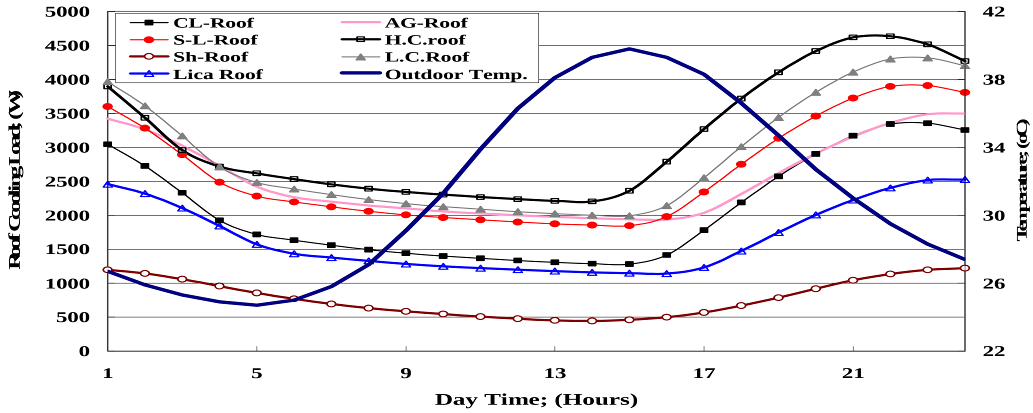


Fig. 13. The hourly variation for roof cooling loads constructed from different building materials.

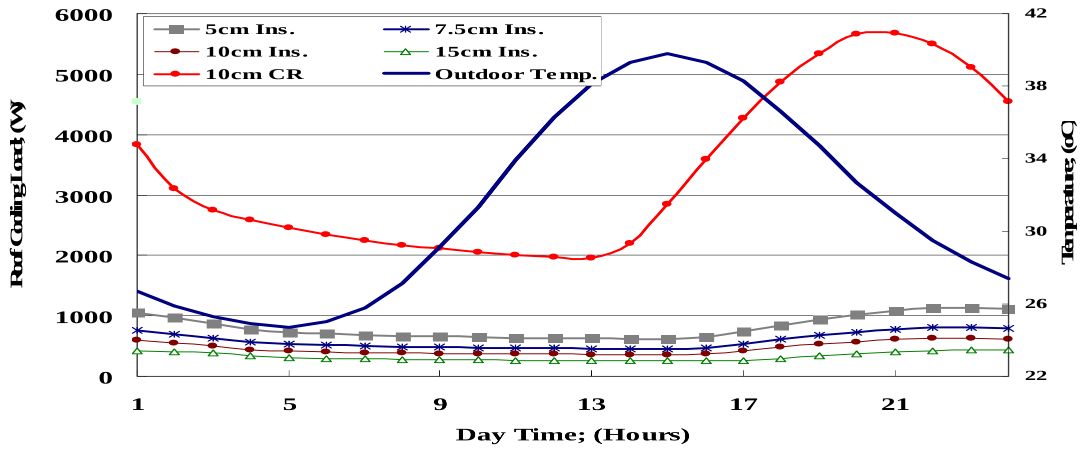
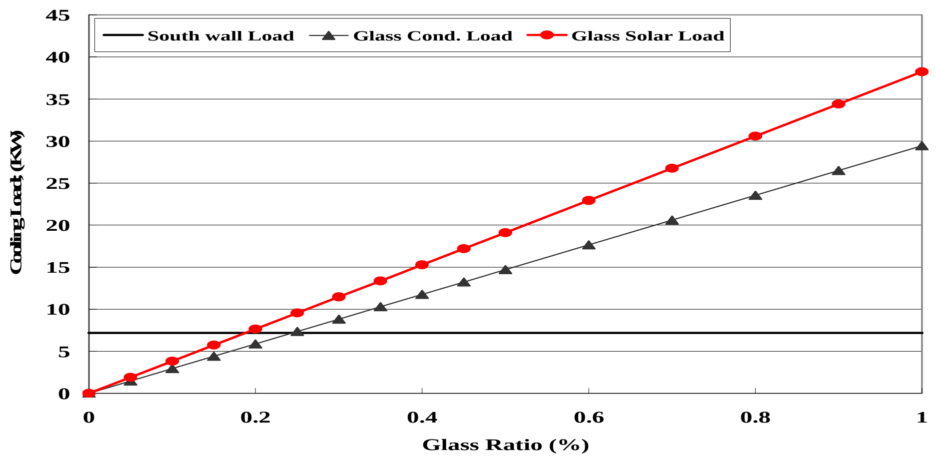


Fig. 14. The hourly variation of the roof cooling loads with and without polystirean layer



. Fig. 15. The cooling load of south wall and window with different glass to wall ratio due to the solar heat gain and conduction

Simulation-assisted evaluation of potential energy savings: Application to an administrative building in France

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Abstract:
The case study presented here falls within a project of feasibility studies to improve the energy efficiency, the carbon footprint and the environmental impacts of several administrative buildings in France.

The first part of the paper briefly presents the data obtained during a classical audit and inspection procedure: the description of the building in term of design, the HVAC system characteristics, the occupancy and operating profiles and the control strategy applied. The second part of the paper gives the first results obtained using an evidence-based calibrated building energy simulation model to analyze the actual building global consumption but also analyze the local consumptions (heat pumps, air handling units, terminal units, lightings, pumps,...).

The last part of the paper then demonstrates the possibilities given by the building energy simulation model to evaluate potential energy saving scenarios through different examples. The advantages and drawbacks of the applied methods and tools are also discussed.

Keywords:
Building energy simulation, potential savings, ECO, audit

1. Introduction

While our economy is heavily dependent on energy resources, the building sector is directly involved. European Union’s countries regulate more and more strictly the construction, renovation and management of their buildings. The building sector represents by itself 40% of the European energy consumption. Non-residential buildings are an important part of the energy consumer and are part of a great challenge for the next decades. As national and local regulators are showing more and more their desire to push in the future years and decades for more energy efficient building through directives like the Energy Performance of Buildings Directive (EPBD, 2002), they are also starting to directly integrate their directive into action in their own administrative building.

Building energy simulation (BES) models are of a great help when analyzing energy use and assessing energy conservation opportunities in the frame of the energy audit of an existing office building (HARMONAC, 2010). Using BES models to help in understanding the thermal behavior of an existing installation requires the BES model to be able to closely represent the actual behavior of the building under study. The calibration of a BES model to an existing situation involves using as-built information, survey observations and short and/or long term monitoring data to iteratively adjust the parameters of the BES model. Obviously, after the calibration process, the tool can be used to identify at first the main energy consumers and then to evaluate some energy consumption opportunities (ECOs). The present paper can be divided in three parts.

In the present work, a simplified BES model and an associated audit methodology have been developed in the frame of several successive research projects (AUDITAC, 2007) (HARMONAC, 2010) and thesis (Bertagnolio, 2012). The Building-HVAC System global model presented here includes simplified models of building zone and of HVAC equipment. The development and the implementation of this BES model are briefly discussed in the first part of the paper along with the audit methodology (including data collection issues) and the calibration process of the BES model.

The second part of the paper presents the main findings of the application of the developed model and methodology. The case study presented here falls within a contract of feasibility studies to improve the energy efficiency, the carbon footprint and the environmental impacts of several administrative buildings in France. Each building study is subdivided into 3 phases which two of them involve the use of a building energy simulation model.

The phase 1 consists in obtaining a calibrated building energy simulation model using data collected by a consulting firm from as-built files, utility bills and on-site tests and measurements. The phase 2 then uses the calibrated building model to simulate various individual technical solutions or ECOs at first, and then some overall concepts scenarios. Finally, the phase 3, the preliminary design, aims to clarify and bring the overall concepts held after phase 2 in terms of accuracy on the technical feasibility and execution planning. This third phase is completely realized by the consulting firm and does not involve anymore the BES model. Through this paper, accent will be mainly put on the findings of the second phase even though part of the first calibration phase will be presented.

2. Building description

2.1. Building design

The building has a floor area of 19,000 m², was built in the 80s and is composed of 11 levels. The building is composed of multiform facades oriented:

- South (flat facades, salient angle and convex)
- North and West in several arcs

The facades are of curtain walls type made of aluminum and glass.

The main building houses offices, a few conference rooms that can accommodate around hundred people, bathrooms and a nursery.

2.2. HVAC system

2.2.1. General principle

The main HVAC production system in the building is composed of reversible geothermal heat pumps, producing hot and chilled water simultaneously, when needed, to satisfy the cooling needs of IT rooms all year and heating and / or cooling of all other spaces throughout the seasons.

The meeting rooms and the other large volumes are only served by CAV air handling units while the office spaces are served by CAV air handling units and 2-pipes fan coil terminal units.

2.2.2. Production

The production of heat and cold necessary to cover the needs of the building is thus fully provided by three similar geothermal heat pumps. In detail, these machine are each composed of 2 screw compressors operating with refrigerant R134-a. The nominal performances of the heat pumps in winter mode and in summer mode are summarized in Table 1 and Table 2.

Table 1: General characteristics and performances of the heat pumps in winter mode

Condenser		
Heating capacity	*Water in-out temperature*	*EER "hot"*
758 kW	*50/40°C*	***4.10***
Evaporator		
Cooling capacity	*Water in-out temperature*	*EER "cold"*
582 kW	*6/11°C*	*3.15*

Table 2: General characteristics and performances of the heat pumps in summer mode

Condenser		
Heating capacity	*Water in-out temperature*	*EER "hot"*
772 kW	*20/30°C*	*5.68*
Evaporator		
Cooling capacity	*Water in-out temperature*	*EER "cold"*
643 kW	*6/11°C*	***4.73***

2.2.3. Air Handling Unit

The building has 17 air handling units for a total of approximately 200 000 m^3/h of supply air according to as-built files. 16 of the 17 air handling units are running since the first commissioning of the building in the late eighties. Some of them allow partial recirculation while some other are equipped with heat pipe energy recovery systems even though some of those systems are in poor condition or even have been removed from the air handling units.

2.3. Occupancy and operating profiles

The building studied here is an administrative building that has atypical occupancy and operating profiles. The number of occupant can vary from 135 to more than 600 depending on the period. These different types of periods will be referred in the rest of the paper in term of week as work period (WP), pre-work period (PrP) and post-work period (PoP).

This unusual use of a building is a major issue in term of building operation but also a major challenge in term of potential savings especially during the PrP and PoP where the number of occupants falls down to nearly 20% of the normal WP occupancy.

In term of schedules, 5 air handling units and the fan coils are working from 6am to 11pm only during WP, are shut off during PoP and restarted during the week of PrP.

The 12 others (about 75% of the total supply air) are working round the clock during the WP. 7 of those 12 even run round the clock during PrP and PoP, the 5 other being started during the PrP week and stop at the end of the WP.

2.4. Control strategy

From the inspection procedure a first observation can be made regarding the control strategy implemented by the building managers. The building management systems BMS is poorly utilize. The system operator rather prefer the principle of the daily round and of starting and stopping of an important part of the installation then the implementation of schedule in the BMS, leaving these system working round clock sometime a whole week before the WP.

In term of indoor setpoint, the setpoint is fixed at 21°C in winter and 22°C in summer in theory during occupation hours but each office is equipped with potentiometer present on the controller of the terminal units allowing a -3°C or +3°C deviation of the setpoint. No inoccupation hour’s setpoint were found from the inspection procedure leading to observation that occupation setpoints were operational all year long even though it appeared as in as-built file the setpoint was 16°C and 28°C in winter and summer.

The humidity setpoint is according to as-built data fixed 40% and 60% +/-5%.

3. BES Model

3.1. Simulation tool

In a building, monthly energy bills cannot accurately analyze the behavior of a building. It is particularly difficult to distinguish the power consumption due to HVAC systems from the other items consumption. BES models, as mentioned before, give a large range of possibilities at the different phases of an audit. In the frame of two different projects, AUDITAC and HAMONAC, a simplified BES model called “SIMAUDIT” has been developed (Bertagnolio, 2012) and tested on a few test cases (Bertagnolio et al., 2008) (Bertagnolio and Lebrun, 2008). SIMAUDIT is a quasi-steady state hourly simulation where cooling, heating and latent loads computed by the building multi-zone model (Fig. 1) are summed and converted into system loads and then, into final energy consumptions (Fig. 2).

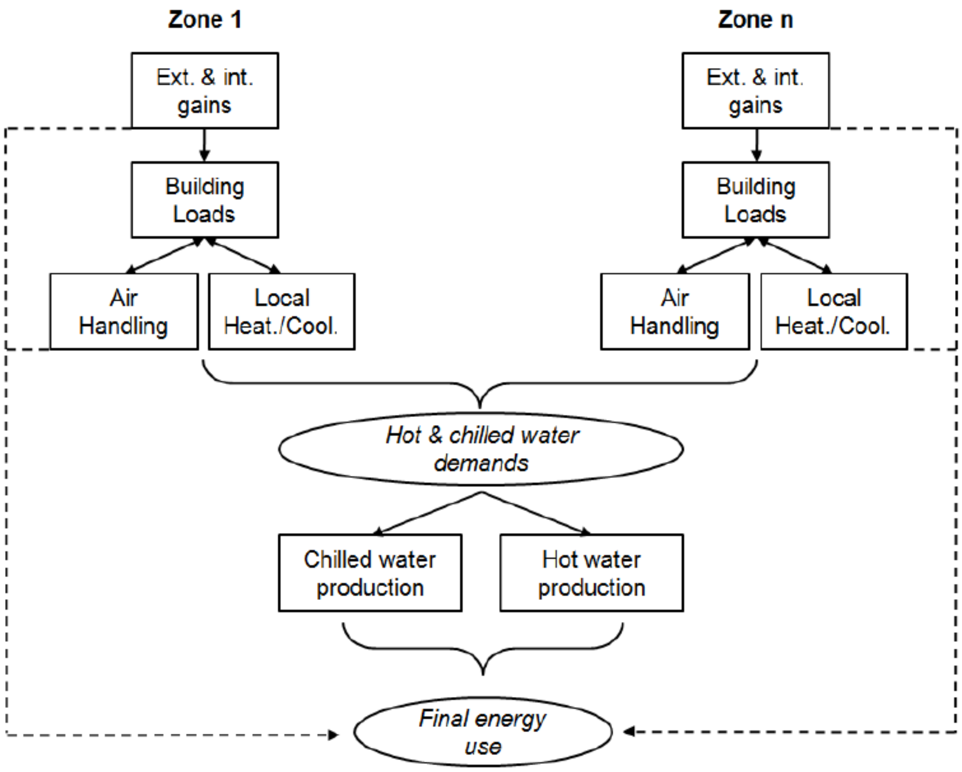

Fig. 1. Multi-zone modeling scheme

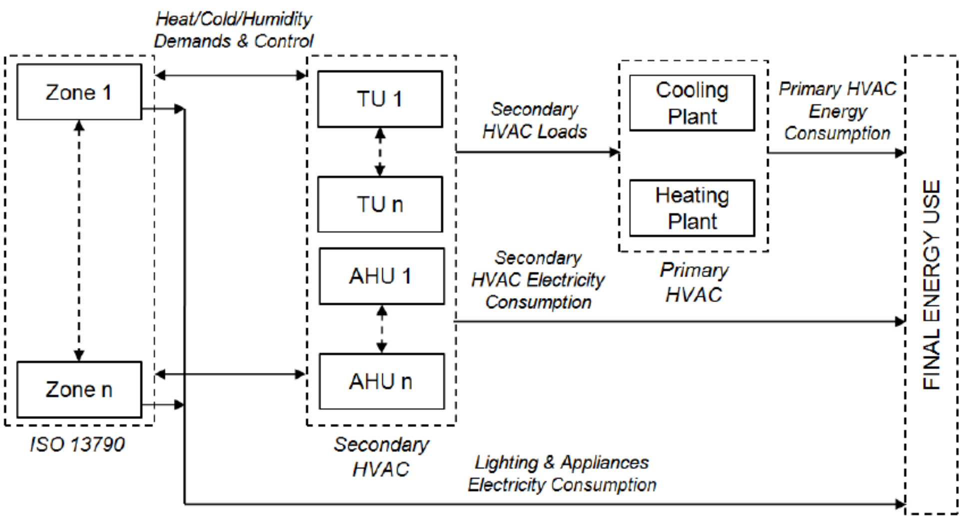

Fig. 2. Global building-HVAC model block diagram

Disaggregation between different items of power consumption can be achieved by means of the tool SIMAUDIT representing the actual behavior of building and HVAC systems.

The first phase of the audit concerns the calibration of the tool. This calibration uses monthly energy consumption, as well as the characteristics of the building envelope, HVAC equipment and their regulation obtained during the inspection of the installation. Other parameters, such as ventilation rates should be adjusted iteratively if no objective information is available. Iterations required to calibrate the simulation model are part of the audit process and to identify the variables to measure or quantify in priority and to highlight important features of the building.

Once calibrated, SIMAUDIT must be able to reproduce with a given precision the monthly electricity consumption according to ASHRAE 14-2002 guidelines (ASHRAE (2002)) by two distinct criteria: on one hand, the criterion of "Mean Bias Error" (MBE) and on the other the criterion of "Coefficient of Variation of the Root Mean Square Error" CV (RMSE). The second criterion is inseparable from the first because of its possible compensation differences (positive and negative) skew the results.

$$MBE = \frac{\sum_{i=1}^{n}(Q_{pred,i} - Q_{data,i})}{n\, Q_{data}}$$

$$CV(RMSE) = \frac{\sqrt{\frac{\sum_{i=1}^{n}\left(Q_{pred,i} - Q_{data,i}\right)^2}{n}}}{Q_{data}}$$

Q_{data} is the average measured value (here on a monthly basis) during the period, $Q_{data,i}$ is the measured value for the “i” period and $Q_{pred,i}$ is the predicted value for the “i” period. It is obviously desirable to minimize the value of these two parameters, the MBE and CV (RMSE) to refine the calibration. In the case of an assessment on a monthly basis, ASHRAE recommends limits of + / - 5% for MBE and + / - 15% for the CV (RMSE).

3.2. Calibrated model and results

The data collected on site and as-built files (plans, technical sheet...) allowed defining the zoning of the building according to its geometry, orientation, HVAC system configuration and use of the various areas. After setting the 9 zones of the building, the geometric description of each zone has been entered in the simulation program.

Available information on the components of the HVAC system and internal loads (occupancy, lighting, computer equipment ...) and on-site measurements were then used to calibrate the model parameters gradually and approach profiles consumptions recorded in 2009.

Figure 3 and Table 3 shows a comparison of monthly predicted and measured consumption values and the corresponding MBE and CV (RMSE) criteria.

Table 3: MBE and CV (RMSE) criteria

	[%]
MBE	3.7
CV(RMSE)	1.1

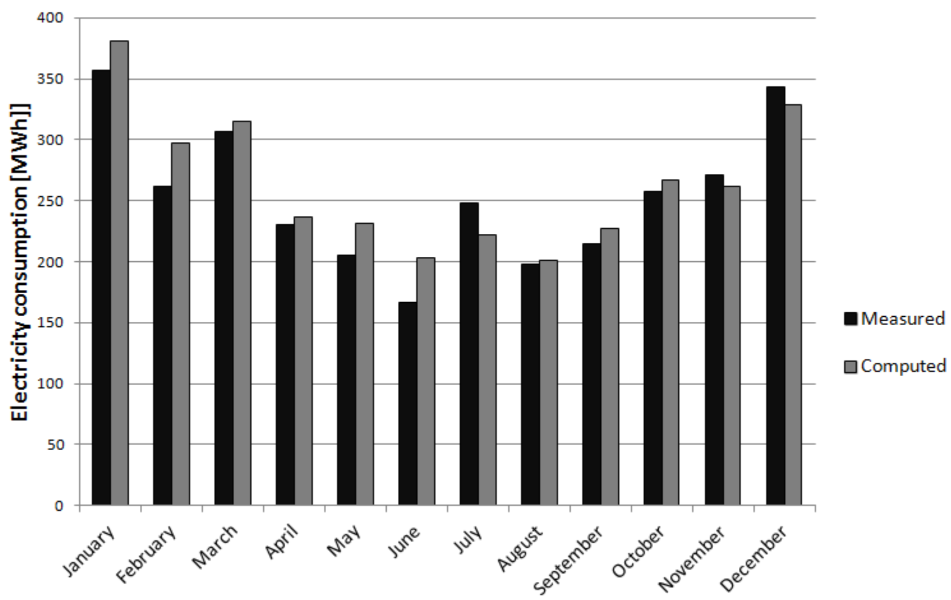

Fig. 3. Monthly measured and computed consumption values comparison

From Table 3, it can be seen that MBE and CV (RMSE) criteria are under recommended limit according to ASHRAE Guideline.

A comparison on an hourly basis, on Figure 4 for the month of January, shows the good representation of the BES model compared to actual measured values.

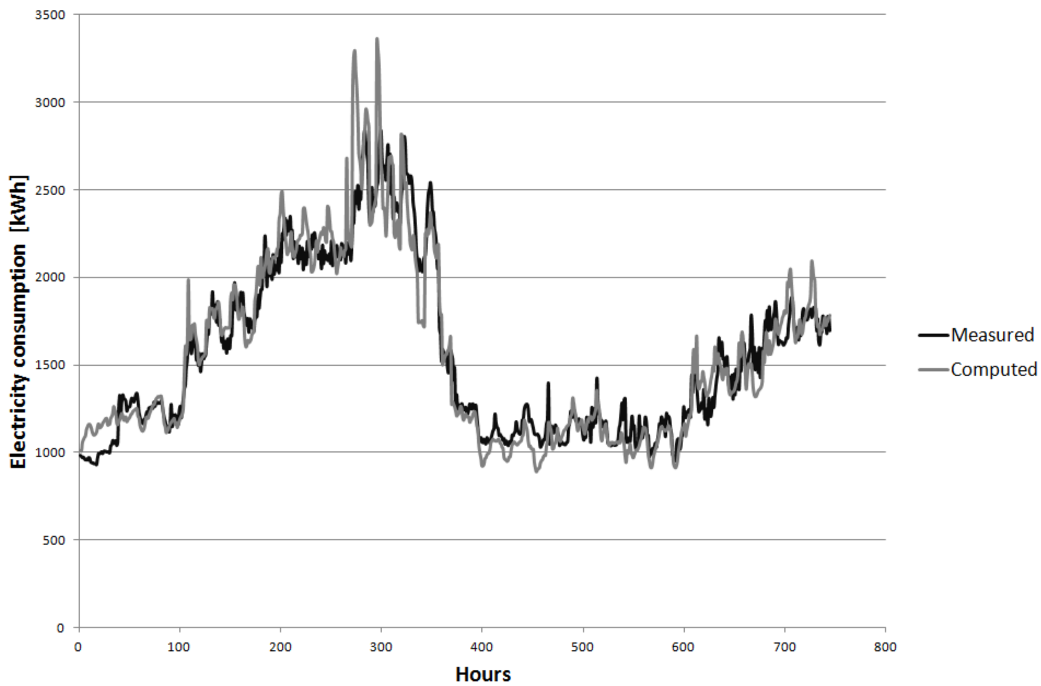

Fig. 4. Hourly measured and computed consumption values comparison

Once the model is calibrated, the consumption of the building can be disaggregated into its different main consumers and analyzed for further potential energy savings phases. Figure 5 shows the disaggregation of annual electricity consumption into the main consumer. It shows the importance of the heat pumps, the distribution, humidification and the ventilation in the building, which all together account for more than 70% of the whole building consumption.

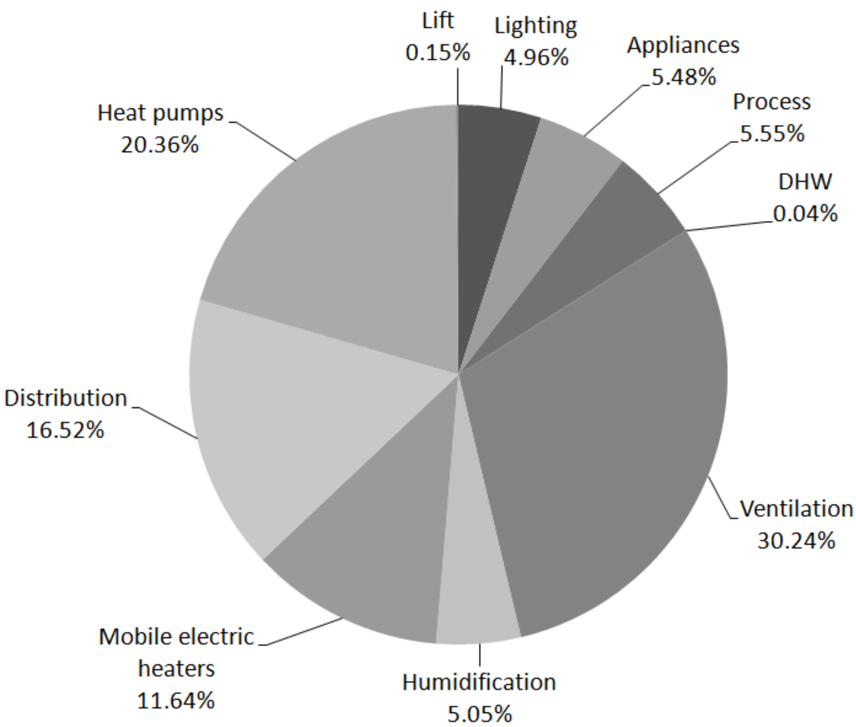

Fig. 5. Desegregation of annual electricity consumption of the building into main items

Also, in Table 3, it can be seen that only 28% of the annual energy consumption comes from the working period. These observations lead to various energy savings scenarios.

Table 3: 2009 Electricty consumption period disaggregation according to SIMAUDIT model

	%	**MWh**	**Primary Energy [MWh]**	**CO2 [T]**
Post-work period (PoP)	50.16%	1591.10	4105.04	119.33
Pre-work period (PrP)	21.81%	691.78	1784.79	51.88
Work period (WP)	28.03%	889.05	2293.75	66.68
Total	100%	3171.93	8183.58	237.89

4. Retrofit options simulation

4.1. Individual technical solutions and ECOs

4.1.1. Efficient schedule implementation in BMS of air handling and fan coil units

The first energy conservation opportunity (ECO) presented here concerns the implementation of energy efficient schedule and setpoint for air handling units and fan coils into the BMS. This would allow a significant reduction of energy consumption in terms of ventilation, heat pumps, humidification and distribution especially for the PrP and PoP where some of the HVAC systems where still working 24/7.

The results presented in table 4 shows an impressing relative saving of 21% of annual electricity consumption.

Table 4: Efficient schedule implementation in BMS simulation results

	Unit	Reference	Solution	Relative Gain
Total electricity consumption	**MWh**	**3 770.18**	**2972.74**	**21.2%**
High peak electricity consumption	MWh	180.49	140.08	22.4%
Winter peak electricity consumption	MWh	1 042.33	842.35	19.2%
Winter off-peak electricity consumption	MWh	730.57	531.28	27.3%
Summer peak electricity consumption	MWh	1 098.85	904.61	17.7%
Summer off-peak electricity consumption	MWh	717.94	554.41	22.8%

Table 5: New functional organization simulation results

	Unit	Reference	Solution	Relative Gain
Total electricity consumption	**MWh**	**3 770.18**	**3577.33**	**5.1%**
High peak electricity consumption	MWh	180.49	172.22	4.6%
Winter peak electricity consumption	MWh	1 042.33	999.77	4.1%
Winter off-peak electricity consumption	MWh	730.57	691.41	5.4%
Summer peak electricity consumption	MWh	1 098.85	1041.50	5.2%
Summer off-peak electricity consumption	MWh	717.94	672.42	6.3%

4.1.2. New functional organization

The second ECO presented here show the possibility of SIMAUDIT to analyze the impact of a modification of the occupancy by zone. In the present ECO, the consulting firm has imagine a new functional organization of the building, regrouping the permanent worker into specific zones instead of leaving them all over the building as it was in the actual organization. This allowed the shutting off of some AHU and fan coil units. This ECO was analyzed independently, without any other changes in the building operation.

4.2. Overall scenario

The final scenario presented here incorporates the most interesting individual technical solution studied in the single retrofit simulation phase according to the consulting. This scenario contains new setpoint during occupation and inoccupation period, a complete implementation of schedule in the BMS, the replacement of some of the AHU with new ones with recovery systems, modification of the functional organization, replacement of some of the lighting and installation of solar shading device.

This scenario presents according to the BES model a potential energy savings of 48.7% of the annual electricity consumption.

Table 6: Scenario simulation results

	Unit	Reference	Solution	Relative Gain
Total electricity consumption	**MWh**	**3 770.18**	**1 932.64**	**48.7%**
High peak electricity consumption	MWh	180.49	92.36	48.8%
Winter peak electricity consumption	MWh	1 042.33	538.50	48.3%
Winter off-peak electricity consumption	MWh	730.57	309.28	57.7%
Summer peak electricity consumption	MWh	1 098.85	661.26	39.8%
Summer off-peak electricity consumption	MWh	717.94	331.25	53.9%

5. Conclusion

BES model can be a great help in energy audit for both analyzing the actual behavior and consumptions of a building and for evaluating the potential energy savings. Difficulties lie in the calibration of the model to the actual building behavior, calibration directly linked to the quality of the data available but also the communication between the consulting firm and the modeling team. The present study demonstrates the usefulness and the range of possibility of such study but has also met difficulties due to the lack of knowledge of both the building operator and the building owner leading to an important energy waste from mismanagement of installations in theory yet effective.

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The Role of the Owners Rep for Energy Performance and Control

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Abstract

Many energy performance projects are unsuccessful due to a variety of confounding issues but most of them stem from the owner's lack of developing a solid team, a strong set of criteria for success, and a mechanism to ensure implementation success. Too often the owner is not the expert and is trying figure it out as they go. There is a severe lack of training and knowledge regarding how to ensure a positive energy reduction plan, how to measure ongoing success, and how to ensure the owner has complete ownership of their systems.

The owner's representative can help by ensuring proper standards and specification documentation are created prior to the RFP stage. During the RFP process the rep can provide a check and balance between the set of specs and submittals. Owner reps can provide independent expertise and ensure vendors and system integrators are complying with the requirements from submittal to commissioning to verification.

Energy performance has a strong reliance on the installed control system. Too frequently energy conservation focuses on a limited scope, typically HVAC. By taking a more holistic view, the owner can implement a more complete solution addressing HVAC, lighting, plug load, equipment and process control and more. Additional areas of possible savings include outdoor/parking lot lighting, irrigation, pumps/motors, integrated user interfaces, common visualization and reporting tools, and more. With a broader evaluation of energy usage and the control environment, owners can leverage the implementation of a facility-wide energy reduction plan using open controls technology that bridges many sub-systems and opens the door to continuous commissioning and ongoing reductions.

In order to accomplish this, a team of affected parties must come to the table and share their pain points and agree to work together to establish and ensure a workable plan. Setting realistic expectations and mechanism to quantify results is an important upfront task. Too often an important entity is missing from the equation such as the IT department or the maintenance department. Project failures are typically not due to technology, they are due to people. Keeping the team on track, managing communication and concerns can be an integral part of an owner's rep.

Training is another very important element of a successful project. Whether it's the facility maintenance staff, the energy manager, or the facility director, each group needs to not only understand the plan, but have training on the control processes, systems, and operation. Formulating a broad, ongoing training program can be a valuable contribution offered by an owner's rep.

Keywords

Automation, control, energy, networking, specifications, standards

Starting Point

Building automation, control, and monitoring systems arguably are at the core of any facility master plan. Whether the project is new construction or a simple retrofit, some effort must be put into how the various systems and operational requirements will interact. Often called system integration, the responsibility often falls under the domain of the controls contractor to figure out how and who is responsible for "making everything work". Significant effort is typically put into the performance and feature sets with less focus on the system functionality and integration.

There are several key initial questions to ask: What are the objectives? Who are the responsible entities? And what is the vision for success? Corporate or institutional visions can be large or small, simple or all encompassing. They can relate to green, carbon footprint, energy, performance or other key goals. Each of these can relate to cost savings, operational improvements, occupant comfort and performance enhancements, or simply system expansion and growth opportunities.

Vision Setting

Starting off with a solid vision and key objectives is not only helpful, but leads to more successful projects. Having an agreed upon vision that matches corporate or institutional goals will enable management to better track and implement objectives.

Developing a vision for a project is crucial and need not be a lengthy, involved process. It can simply be an extension of the overall organization plan. If an organization's plan is to reduce costs, reducing facility costs is a natural progression from reducing production costs. If a corporate goal is to be more "Green" by implementing green best practices such as recycling, carbon offsets, and energy usage reduction, a facility vision might be to reduce facility energy costs by implementing industry best practice. If corporate vision is to improve worker productivity and performance, a facility vision might be to reduce occupant complaints and improve environmental conditions.

Whatever the corporate objectives are, a facility master plan vision should be a natural extension and can encompass actionable objectives that mesh with budgets and team skill sets. Here are some examples of vision statements that will lead to goals, objectives, and actions:

Improve our customer experience by addressing occupant comfort and performance issues

Reduce corporate facility energy costs by implementing industry best practices for system optimization and control

Implement green strategies in alignment with our corporate goals and demonstrate ongoing improvement to our environments

Achieve better cost control by addressing our facility costs, ownership, and expertise issues.

Vision setting enables the team to point to the big picture and gauge their activity and actions against a benchmark and allows them to answer the question: "Is what I'm doing in alignment with the vision?"

Leadership and Engagement

Having a vision is meaningless unless there is a plan in place and leadership commitment to achieve the plan. Leadership starts with key management, but extends to department heads and key staff members. In fact, a great plan can be scuttled by a staff member that is not on board and resists implementation or obstructs the process. This can be out of a fear for their job or career growth or any number of other reasons.

It is critical to ensure acceptance and adoption by all team members and there be a high level of accountability and communication to this effect. Setting personal and team objectives along with identifying gaps in expertise is important and key to success. A great plan without the knowledge and experience to implement it is destined to failure.

Stay engaged through frequent review and communication. Periodic evaluations against objectives will help not only achieve the goals, but keeps the team engaged and ensures accountability. Having a single meeting that establishes a vision and objectives with not follow through will not be successful. Ongoing evaluation, modification, and progress tracking will help the team adapt and stay engaged. Highlighting successful achievements is often more important than belaboring weaknesses and shortcomings.

Teaming

Who are the players? A good plan must have a qualified and engaged team involved. When facility system construction or retrofit plans are adopted there are many affected departments and entities both internal and external. Here is a list of some of the players:

- Internal
  - Facility Management and Engineering
  - Energy Engineering
  - Construction
  - Operation and Maintenance Departments including Electrical and Mechanical
  - Information and Data Management - IT
  - Security (life safety)
  - Corporate or Institutional Management
  - Contracting, Budgeting, and Finance Departments
- External
  - Mechanical, Electrical and Controls Contractors
  - Master System Integrators
  - Project Managers
  - Architects

Consulting Engineers

Product and System Vendors, Distributors, VARs

Systems

It is also very important to identify what systems or sub-systems might be involved or affected by the plan. A typical facility has a wide range of systems and their associated team member responsibilities. A representative list includes but is not limited to:

HVAC – including chillers, air handlers, VAV systems, economizers, cooling towers, etc.

Lighting - including indoor, high-bay, emergency, facade, walkway, parking lot, and roadway lighting

Energy Management - including metering, sub-metering, and load management

Power Systems - including generation, cogeneration, and renewables

Life Safety Systems - including laboratory fume hood, smoke evac systems, fire detection, suppression, toxic gas monitoring, CO2 monitoring

Elevator/escalators

Process Control Systems

Security and Access Control Systems

Audio/Visual Systems

Water Systems - including irrigation, hot water/cold water, waste water

Alarming and Annunciation Systems

Occupancy and Vacancy Systems

Monitoring, Control and Reporting - Including user interfaces, alarming and alerting, trending, scheduling, data analysis

IT and Data Systems, LAN, WAN, VPN and related systems

Certainly not every one of these systems in effected in most cases, however it is critical to assess which systems are in play for a particular project and who owns that area of responsibility. Identifying gaps in expertise or responsibility early will establish the potential viability and success of the project.

Commitment to the Vision – Are you on the bus or off?

Once the team members and systems are identified, working with the responsible parties to ensure their commitment, capabilities, and follow through is required. When interviewing team members, both internal and external, gauging their level of proficiency and experience toward the stated scope and objectives will determine who and who is not supporting the objectives. Consider holding a team meeting to present the vision, scope, and team objectives and get commitments from all to comply. Ongoing verification and validation is required to ensure success.

Leadership Team

Subject Matter Experts or SME's contribution to the overall vision is extremely important to the overall success of a project or vision. Ensuring the right people are brought in and engaged early will alleviate many future problems. From a psychological viewpoint, people like being asked their opinion and are typically willing to engage positively when asked.

On the other hand, when a person's area of expertise is affected by a project and they are not engaged, danger looms. Underhanded or subversive actions can scuttle a project very quickly.

Identify the SMEs necessary for success and ensure they are engaged, committed and own the outcome of the project. Having the leadership team onboard will smooth the path for their departments acceptance and engagement and should yield a more positive outcome.

Overview Scope Document

Having a documented overview of the vision, objectives, and targets in the form of a "Scope Document" is highly recommended. Think of this as the executive summary stating the key elements of the plan, the timing, team requirements, phases, budgeting, technology, architecture, affected systems, and any other key elements ensures existing and new team members have a reference point.

Scope documents are also helpful when working with outside entities such as contractors, consultants, and vendors. Obtaining team understanding and consensus to a scope will help set the bar for future stages such as compliance to specifications, standards, and proficiency requirements.

Scope documents are living, breathing documents that should undergo periodic updates and enhancements. Dependencies such as technology changes, standards changes, code changes, best practices, and scope enhancements need to be considered on a regular basis. Additionally the success or failure of a particular project might be important to capture within the scope as it pertains to the objectives. It makes little sense to include an element in a scope that is cost prohibitive, can't be implemented technically or logistically for some reason, or becomes outside the vision. Managing the process to a core set of objectives is critical but equally critical is the assessment of those of objectives and ongoing refinement.

Developing Corporate Standards and Guide Specifications

Once the overall scope is developed, often the next level of detail includes integrating corporate objectives - green, energy efficiency, transparency, kiosks, carbon offsets, occupant comfort and productivity into a set of “Corporate Standards” and “Guide Specifications”. These documents are developed to ensure the basic tenants are being met with each new project and that local teams have a starting place to work from. Guide Specs and Standards enable teams to develop their projects according to the best practices set up by the leadership team.

Corporate Standards typically include the communication infrastructure and architecture, technology preferences and requirements, performance and functionality requirements, safety and security requirements, and reliability best practices. This might be as simple as ensuring the computers that are used are specified to be the latest processors and software, to more complex issues such as cross system communication interoperability standards, competive bidding standards, and system user interface standards. Some go as far as to define a set of common user interface graphics and dashboards that force integrators to comply to a corporate look and feel, naming convention, and password/security access.

Security Standards

Interfacing with the corporate IT infrastructure requires significant compliance measures and understanding in order to ensure safe, reliable, and secure access to the myriad of systems. Typically IT professionals are not well acquainted with facility systems and vice versa. Taking some time to familiarize each team with the key pain points, objectives, and issues early will help speed the process and reduce the frustration later on in a project.

Safety Standards

There are several issues regarding safety that need to be addressed. They include occupant safety, staff safety, and process and equipment safety. Overall standards should include some basic information about compliance, code issues, and levels of safety requirements. One element of a safety standard might include alarming/alerting information being sent to the on campus security office to alert them of a potential issue. Systems that can generate these high priority alerts need to be identified and personnel need to be informed of the required action should an event occur.

Publication, Promotion, Training

Once the scope documents, corporate standards, and guide specs have been created, the next step is to ensure the relevant parties are aware of them, encouraged to comply or held accountable, and are properly trained. Good standards are a waste of time if they are not implemented or misunderstood. They should be merged into a corporate training program providing basic education, direction, requirements and responsibilities.

Managing a staff continuing education program can be extremely beneficial to both seasoned veterans and new hires as well. Providing an overview of both the core job requirements and corporate objectives along with any adjacent job knowledge can be helpful. As an example, an HVAC tech should also know a bit about energy management, security, and safety. An energy manager should know something about all of the basic energy consuming sub-systems such as lighting, HVAC, data-centers, metering, and commissioning. Establishing a continuing education program supported by each department that provides an overview of the affected systems, key pain points, and key objectives can help with team building and team management.

Challenges

Lack of staff support for key objectives, lack of proper education and compliance requirements are some of the key challenges. Additionally having a gap in ability of the staff can be a major hurdle. Understanding the SMEs and their staff’s abilities and their gaps can be an effective evaluation exercise as part of this vision and master planning exercise and should be considered as a key task.

Achieving compliance to the developed standards is major task if the new standards are outside the comfort zone for both staff and vendors/contractors. Effort must be taken to address concerns and to what level of compliance a vendor/contractor will be held accountable. A good spec is worthless if a supply is allowed to provide a non-compliance product or system simply because their price is 5% cheaper. Often the cheaper product comes at a much higher price down the road.

So, the contracting office must also be on board and a team to review submittals and procedures must be in place. Submittal verification and compliance is a lengthy topic, worthy of another paper at a later date. Suffice it to say that a simple compliance check list and verification documents can force vendors to sign off and be held accountable for their solution.

Now that we've reviewed the key elements in a good master facility plan, the key personnel and the areas of attack, by far the biggest challenge facing many organizations is the lack of a dedicated person or department head to take the lead and help guide the process. Enter the Owner's Rep

The Owner's Representative

The Owners Rep provides external task oriented leadership and support for both small and large scale master planning projects. The owners rep can help an existing team move through the process or help build a new team and get them started.

The Owner's Rep should be objective, neutral, and motivated. They should have a broad understanding of the master planning, scope, spec, and standards process and also be able and available to support the leadership team with all or most of the issues and topics listed above.

Qualifications of the owner's rep should include:

1. Independent – not tied to a particular vendor, product, or system approach
2. Experienced – background in control, networking, facility systems, market and technology, able to advise on all aspects of the master planning process
3. Professional – providing team leadership, quality reporting, objective setting, facilitation through the process
4. Supportive– able to listen, digest, and assimilate the high level master plan objectives and also be able to deal with low level issues
5. Networked – able to bring in SMEs as needed into the process should the need arise

Responsibilities of the owner's rep can include:

1. Scope, standards, and guide spec support and development
2. Training program needs identification and development
3. Working with vendors and industry to ensure compliance
4. Evaluating open systems technology, standards, and approaches that are "owner focused"

5. Supporting fair competitive bidding best practices by developing guide specs that are non-proprietary and non-sole-sourced
6. Coordinating internal and external teams to establish ability and commitment
7. Reporting, documenting, and baselining the planning process
8. Evaluating technology approaches and solutions against industry best practices
9. Working with commissioning agents, procedures, and requirements
10. Understanding of costs, timing, quality, and reliability requirements

The owner’s rep can help with the overall process by providing guidance for action steps including:

Evaluating where are we and where do we want to go?

Interviewing the leadership team to uncover key issues, objectives and expertise

Provide a “Knowledge Gap Analysis” - What do we know, what don't we know?

Establish key system and sub-systems affected by the master plan and their levels of required integration and interoperability

Develop Baselining - evaluation of existing system, architecture, issues and identify what needs to be addressed by the master plan

Strategy implementation - starting point evaluation and dealing with installed “legacy” systems. Determining whether to upgrade, retrofit, or integrate with what is already installed.

Determining what level of “Ownership” the owner has over their systems: Do I own my systems? Or does my vendor own me and my systems due to proprietary or contractual locks.

Evaluate Open vs. Closed systems and the benefits and pitfalls of each, helping make an educated plan and approach

Working with vendors to deal with vendor support vs vendor lock-in

Working with the contracts department to evaluate competitive bid, competitive service, or in-house service options

Provide validation evaluation: Compliance to specifications, validation of standards and guide specs. Can industry comply? If not, why not?

Are revisions required to keep up with best practices and technology improvements?

Proficiency - Certification - Education – Qualification

The owner’s rep can help develop the requirements and compliance for vendors, integrators and staff. Examples of some beneficial programs include:

- LonMark Certified Professionals, Certified System Integrators, and Certified Products
- Smart Buildings Institute - Project compliance and training standards
- ASHRAE (BACnet), BOMA, IFMA - standards and best practices
- OpenADR, NIST, Zigbee standards
- And a variety of other industry best practices from trade groups, standards, and associations

Cost Factors

The role of the owner’s rep can be either a short term or long term relationship. Ideally, the owner’s rep, at the end of their contract, will have provided enough guidance and support that the internal team can take over and be comfortable with following through with the plan.

By contracting with an owner’s rep firm, a variety of experts can be brought in as needed to move the planning process forward rather than having to hire full time personnel to accomplish the same task. This can be a significant cost savings and the owner can leverage expertise otherwise not affordable or available.

Summary

Developing a facility, campus and enterprise master plan for energy, operational, and cost efficiency can be a daunting task. But more and more organizations are pursuing strategies that incorporate all elements of the organization. Cost savings are no longer focused solely on manufacturing or process cost reduction. They have to include all aspects of the process, including facilities. Developing a good master plan and vision is crucial, followed by creating plans the supporting documents, education, and execution.

The owner’s rep can help the process and be a cost effective guide through the process. Owner’s reps often have a collection of task specific experts to rely upon for detailed technical support as needed. Relying on trusted external independent support can speed the process and ensure objectives are achieved and the owner’s team is well supported and educated along the way. The ultimate goal is often self-sustainability and this can be built in as part of the master plan.

The risk of buildings overheating in a low-carbon climate change future

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Abstract:
An overheating risk tool that is compatible with building performance simulation software has been developed, using principal component analysis to give a statistically rigorous simplification of the UKCP09 probabilistic climate projections. The tool converts a single dynamic simulation output into many hundreds of simulation results at hourly resolution for equally-probable climates from the UKCP09 weather generator. The result is a population of outcomes for the performance of a specific building in a future climate, thus helping the user choose adaptation technologies that might reduce the risk of overheating. The outputs of the LCF tool can be delivered as a risk matrix or a probabilistic overheating curve. The perceptions and requirements of potential users were assessed and, for non-domestic buildings in particular, the need to quantify and assess overheating risk was understood by professionals, with concerns expressed for the ease of incorporation of the UKCP09 projections into this process. The new tool has the potential to meet these concerns.

Keywords:
Buildings, climate change, overheating, thermal comfort.

1. Introduction

The global climate is getting warmer just as buildings have to meet more stringent carbon emissions targets. Because global warming and climate change are widely accepted as being due to increased levels of greenhouse gases in the atmosphere, governments worldwide have pledged to reduce emissions in order to mitigate the future changes, and this has driven the move towards low carbon buildings that are more highly insulated and more airtight, and use less energy, with an increased proportion of that energy obtained from low carbon sources. Unfortunately, there is little sign of occupants operating fewer energy-using appliances (even if these are driven by low carbon electricity) and the incidental gains from such appliances will be retained in the internal environment of such buildings. Together with metabolic gains from occupants, this leads to the potential for serious overheating, as has been observed in schools, offices and dwellings. Overheating may encourage the use of artificial cooling, where none was needed previously, and this introduces a fresh source of emissions, making it more difficult to meet the reduction targets.

At the same time, the buildings that already exist and those being designed must also continue to perform in the environment over their lifetime of several decades. They will have to be able to adapt to future climates, despite having been designed for current climates. The key contextual questions are whether we have an adequate understanding of what the future climate will be and the extent to which this understanding should guide the design and retrofit of the built environment. The objectives of the work described here were, first, to explore how the latest climate projections can be used in the building performance simulations commonly performed at the design stage in new buildings; second, to understand how building designs can be changed to prevent buildings failing to perform in the future climate; and third, to produce a method that is useful for industry needing to assess overheating.

2. Climate projections

Computer models of the climate have been developed over many years and attempt to replicate the physical processes occurring in the atmosphere (solar radiation, convection etc) and in the oceans (currents, circulation etc) to estimate climate conditions. They are very complicated and intensive in computing power and ultimately predict how the weather variables such as temperature, solar radiation, wind speed and direction, relative humidity, cloud cover will vary with time. Deterministic climate projections, such as those of the UK Climate Impact Programme (Hulme et al, 2002) give a single value of these parameters with no associated indication of uncertainty. These first generation projections are still in use and a so-called morphing algorithm has been used to produce weather data for building design in future climates (Belcher et al, 2005). The latest generation of climate projections – UKCP09 (Murphy et al, 2009) - are probabilistic, giving outputs for different percentiles of probability, or if required the user can obtain all possible iterations of a given scenario (Fig.1). Again, algorithms can be used to interpolate to the required timescale. The UKCP09 projections used in this paper require the user to choose an emission scenario (low, medium, high), the time period of study (2010-2099) and the location (5km grid squares in UK), from which the weather generator outputs hundreds of climate files, each equally probable.

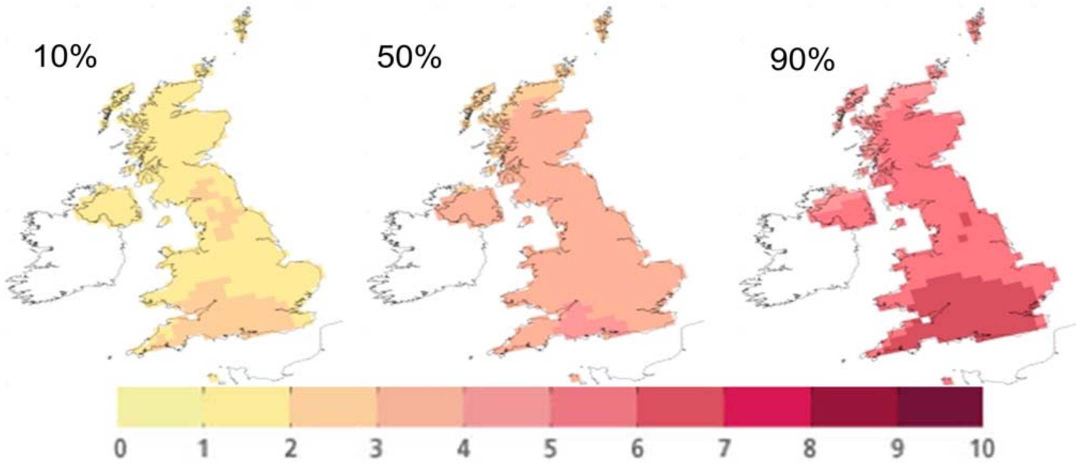

Fig.1: 10, 50 and 90th percentiles of the probability of increase in average temperature (°C) across the UK in the 2080s. The 90th percentile means that there is a 10% probability of the temperature rise being greater than that shown (UKCP09).

3. Building Simulation

Dynamic building simulation is a computationally intensive method of applying physical models for the heat and moisture transfer through the building fabric, solar gain and the effects of occupancy, taking account of interactions and feedback effects, to show how internal conditions in a building vary over time. From information about the external climate, the building construction and services systems used together with the occupancy profile it provides information on the environmental performance of buildings (such as annual energy consumption, running costs, heating / cooling loads, thermal comfort and carbon emissions).

The effect of changes can be investigated and the design optimised. ESP-r, an open source software, was used in this work, but several commercial software packages are available including IES-VE (2012) which was developed from it, and consequently the tool described in this paper would be readily compatible with IES-VE.

4. Development and validation of the LCF tool

4.1. Regression process for weather data

Since dynamic simulation at hourly resolution gives 8760 data points for a single variable (e.g. internal temperature) in one climate over one year, and a large number of climates are needed to establish probabilities, the amount of information rapidly becomes unmanageable and it is impracticable to simulate a building in every possible climate. The solution chosen here is to emulate the simulation process by multiple regression. In summary, 100 climates are chosen at random from the 3000 produced by the UKCP09 weather generator (Jones et al, 2009) for a particular scenario (e.g. high emissions, 2040-2069 time period, chosen location). The weather generator produces an hourly time series for seven weather variables (temperature, precipitation, relative humidity, vapour pressure, sunlight fraction, direct radiation and diffuse radiation). The internal conditions depend on a contribution of each of these variables both at the current time and, through the inertia of the building fabric, a contribution at each of the preceding 72 hours. Therefore there are 504 (=7x72) input weather data points at each hourly value. It is to be expected that there will be correlations between these variables but without making any assumptions about their precise nature, Principal Component Analysis was used to simplify the correlations between pairs of variables (Patidar et al, 2011). PCA is a statistical method for analysis of data with a high number of dimensions, and can transform a large number of variables which are possibly correlated together into a small number of uncorrelated variables. PCA was done in two steps: first, exploiting the correlations within the 72 hours of each individual weather variable, and then exploiting the correlations between different weather variables. This reduced the 504 components to 33 sub-components, made up of 11 for temperature, 6 for precipitation, relative humidity and vapour pressure, and 16 for sunlight fraction, direct radiation and diffuse radiation. The transformed data in the 33-dimension set retained 95% of the total variation in the original dataset (Patidar et al, 2011). Multiple regression was then used to establish a simple linear relationship between the transformed dataset from the randomly selected climate file and the corresponding building simulation outputs. This regression based approach drastically reduced the number of building simulations that must be carried out for a climate scenario, and hence the time taken, and this made emulation feasible.

The multiple regression approach has also proved to be effective for performing a systematic analysis of various aspects of heatwaves, including the frequency of extreme heat events in future climates, their impact on overheating issues and effects of specific measures to offset overheating (Patidar et al, 2012). Indoor temperatures could be correlated with extreme air temperatures in a heatwave, with effects that differ subtly from those obtained by analyzing the effect of an average rise in temperature over a year.

4.2. Application in building simulation

The starting point for the use of the LCF tool is a single dynamic simulation at hourly resolution using ESP-r, IES-VE or similar for a single weather file. This simulation needs to be done afresh for each building version that is to be investigated and yields a results file, giving internal temperatures, heating or cooling loads, etc also at hourly resolution. This single results file is sufficient to calibrate the coefficients in the multiple regression equation. Having specified some information about the building, such as times of occupancy, the assessment criterion (e.g. 1% of occupied hours above 28°C), the form of assessment required (overheating or load analysis) and the chosen future climate scenarios, the user can then run the tool from the weather file and the results file. The tool incorporates up to 1000 weather files from the UKCP09 weather generator for each climate scenario (emissions level and timeline) to deliver hourly results, such as temperature in each zone of the building (Jenkins et al, 2011). These outputs are automated so the user can choose between several graphical or textual formats. The whole process is complete in about half an hour.

Validation of the tool has been carried out on different versions of four buildings by running 100 hourly dynamic simulations and comparing them to 100 hourly regression model profiles that effectively emulate the simulations. In real use, all 100 hourly dynamic simulations are not needed; only the single calibration simulation is necessary and this saves considerable computing time, making the tool a practicable add-on as part of the building design process. Fig. 2 shows the good agreement (i.e. small residual differences) between the emulated results and the dynamic simulation results for a typical house: more than 93% of the hourly temperatures are within ±1.5°C of the simulation (Jenkins et al, 2011).

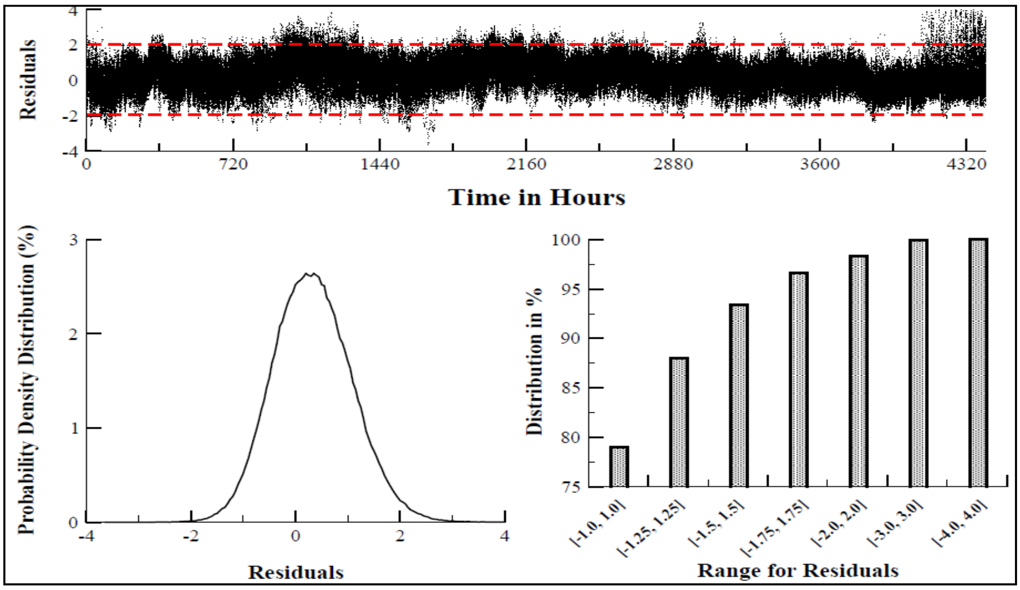

Fig.2: Validation of the regression model for a house in London under the medium emission scenario for the 2020-2049 period, based upon 100 representative weather files. The residuals are the differences between the hourly temperatures estimated by 100 dynamic simulations and by the regression model.

4.3. The LCF tool outputs

As already noted, the tool can provide output in several forms. Fig.3 shows a comparison between a future climate scenario and the baseline performance of the same building in the current climate. It shows the cumulative frequency of the percentage increase of the overheating metric (number of hours over 28°C) compared to the average for the baseline scenario. It indicates that the house has a 96% probability of being warmer if no action is taken, whereas using a simple window opening adaptation reduces this to 72%, and, combined with external shading and reduced internal heat gains from equipment, the probability is further reduced to 14%. An alternative way of understanding this information is to choose a level of risk that might be acceptable for a designer. For example a 90% probability level would cover all but the most extreme results from the tool. If designing to this level for the same future climate Fig.2 shows, with 90% certainty, that the number of hours above 28°C for this building will show an increase of at least 8% when no adaptation is used but a decrease of at most 10% when the windows are opened and a decrease of at most 42% when windows, shading and reduced gains are all employed. Fig.4 shows that the progressively warming climate increases the probability of overheating in the unadapted house, expressed as the percentage of occupied hours above 28°C. Again 96% of climates in the 2080s medium emissions scenario will give more than 1% of occupied hours above 28°C. A further, simpler display of the overheating risk is shown in Fig.5, where the graphical colour-coding corresponds to the value on the vertical overheating threshold line in Fig.4; the value corresponding to 96% of climates in the unadapted house is indicated by the intense colouration in the chart. This also shows other climate scenarios, processed in the same way as the London, 2040-2069, medium emission scenario of Fig.3.

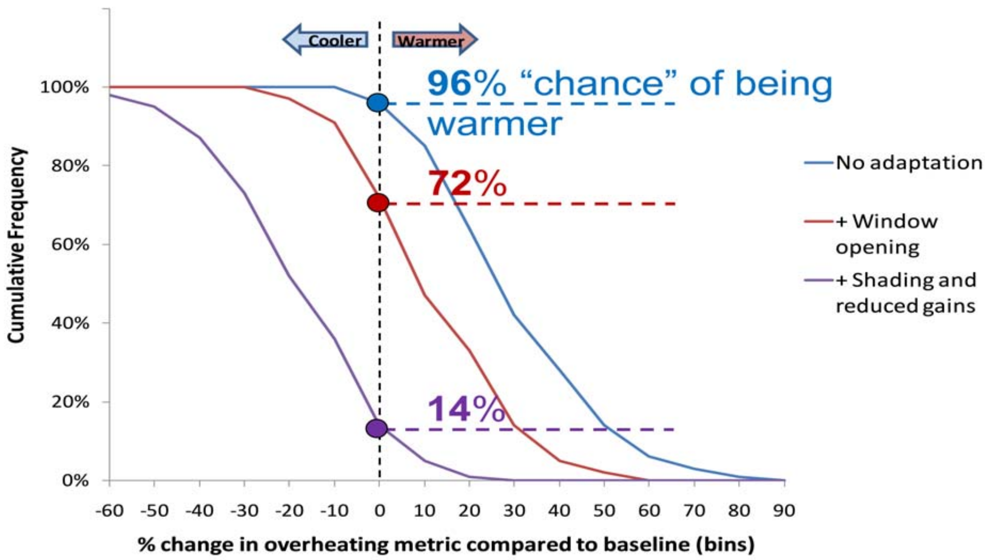

Fig.3: A probabilistic failure curve, showing % change in the number of occupied hours above 28°C for a 3 bedroom detached house in London, 2040-2069 climate, medium emissions.

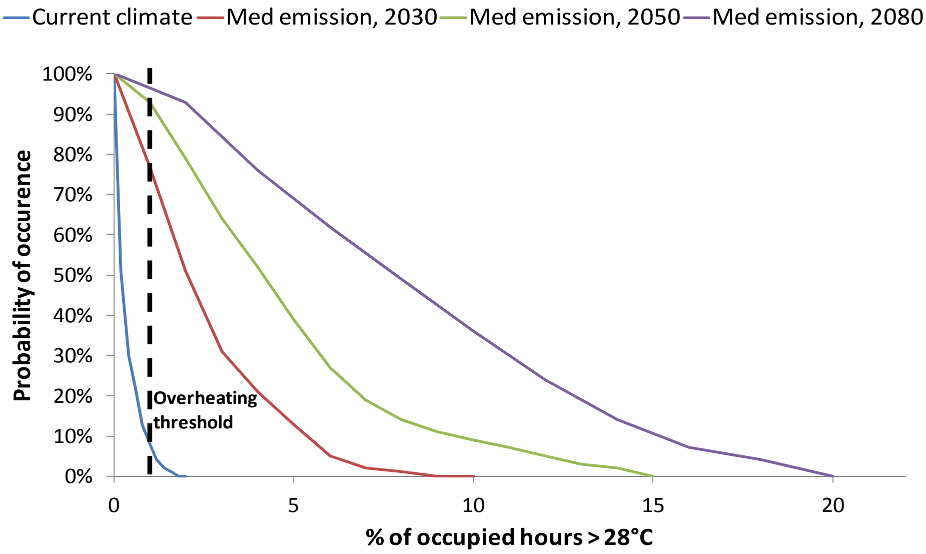

Fig.4: Effect of climate change on the same house as Fig.3 with no adaptation measures used.

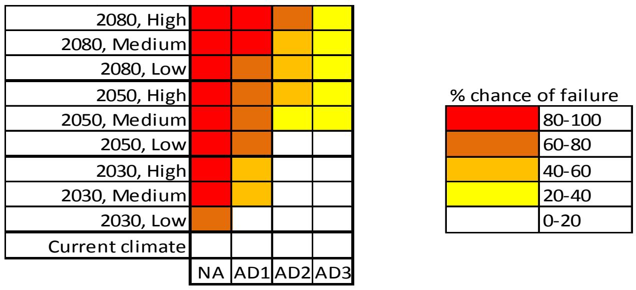

Fig.5: A simplified representation of the data from Figs.3 and 4. NA = no adaptation (baseline), AD1 = window opening, AD2 = AD1 plus shading, AD3 = AD2 plus reduced gains.

5. Relevance to design professionals

A series of focus groups, interviews and questionnaires were administered with professionals working in building design in order to elicit their preferences for the form of a possible design adaptation tool and to translate the outcomes to a practical level. 46 responses to a questionnaire on present building design practice showed that typically buildings are designed to minimize capital cost and to comply with (rather than exceed) current legislation / regulations. Assessment of overheating is not a priority and optimization of performance in a future climate would not normally be considered unless driven by the future occupant (Gul and Menzies, 2012). These themes informed the questions used in focus groups and interviews, in which 41 professionals participated. The research questions addressed whether overheating is seen as a problem, the kinds of climate data, tools and software in current use in building design, use of probabilistic climate projections and the preferred form of an overheating tool (Gul et al, 2012).

Overheating is not currently considered as a risk in the domestic sector but it is seen as increasingly important in non-domestic buildings, with inappropriate fabric, south-facing glazed facades and inadequate ventilation giving concern. However, the typical professional's response is to put in some cooling provision to deal with overheating. Future overheating is seen as a problem for complex buildings and schools, rather than housing, although it is recognized as becoming an issue in new dwellings in southern UK. In the non-domestic sector, something happening in 50-60 years is not high on the industry's agenda and there is minimal concern for future overheating risks, partly because cooling plant is over-sized and, with a limited lifetime, is likely to be replaced before the problem gets serious. Climate data is scarcely used in domestic building design, which is based on the feeling that "it worked last time", whereas non-domestic designers use detailed data if required, in which case CIBSE Test Reference Years are the benchmark, although designers lacked guidance on which climate files to choose. Probabilistic climate projections are perceived as a valuable way to look ahead and allow adapting to future climates but will only be used if required by law, and even then they must be user friendly otherwise there will be limited uptake. Overheating analysis is considered to be a resource intensive exercise that would not always be justifiable to a client, and as a result the domestic sector relies on basic steady state calculations like SAP or PHPP, whereas in non-domestic buildings SBEM (steady state) would be supported by dynamic simulations using IES-VE, TAS, ESP-r, Hevacomp and ClassCool.

Accepting that an LCF tool will be needed eventually, professional preference is for something that can be added simply to existing modeling procedures, which would need to be cost effective, and preferably sit within a single level of expertise within an organization. As a software solution, it might end up being part of the Building Regulations and therefore use the same building specifications as those required for SAP calculations. One professional suggested that "two levels of a tool, one with a high level of information for someone trying to understand the issues, and another simple one that can be used for a report" would be suitable, but another was cynical about the cumulative probability graph (Fig.3) because it would be off-putting to people who struggled with graphs at school. This suggests that the colour-coded display such as Fig.5 might be more appropriate, although this could be given in addition (rather than as an alternative) to the output shown in Fig.3.

6. Discussion

The LCF tool has proved to be useful and efficient in carrying out the overheating analysis of naturally ventilated buildings, for which it was originally designed. In this situation its delivery of temperature in the different zones of a building at hourly resolution enables it to assess the probability of failure, expressed in terms of the percentage of occupied hours above a threshold temperature. However, it works equally successfully for the analysis of cooling and heating loads in mechanically ventilated buildings, where the failure criterion is more difficult to define. For example, neither cooling nor heating plants are normally sized to close tolerances, so an increase in cooling load is only likely to result in a higher number of hours of operation and a decrease in heating load is likely to result in lower heating plant efficiency. Neither of these are clear cut 'failures' but the LCF tool could be applied to assessment of cooling energy consumption and associated CO_2 emissions.

Further validation on more buildings and using different adaptation technologies will be needed in order to test the limits to application of the tool, and based on feedback from potential users different forms of output can be tailored to be more specific to the needs of particular clients. The format chosen for the improved interface will depend on whether the tool is to be used as an open-source, stand-alone model or within existing building simulation software or used as a consultancy tool by the developers. It is recognized that it would not immediately be a routine tool for every design, but rather an additional analysis that some clients might value. However, its potential will be realized in the future, when deterministic climate projections are recognised to be no longer adequate. It is difficult to imagine that subsequent generations of climate projections after UKCP09 will revert to deterministic forms, and probabilistic projections will eventually be accepted as normal, whereupon the LCF tool could be adopted as the industry standard.

Since the tool can run multiple weather files for the same building, it is compatible with other climate projections and it could be useful for the study of other climate variations like locations, micro-climates and altitude or coastal factors. The advantage of the tool is that a single building simulation is all that is required in order to carry out sensitivity analysis on these factors.

Finally, as hinted at above, the failure analysis can be converted into an energy analysis in order to answer questions on the most probable energy consumption of a building for a given future climate scenario. This could be done at a single building scale or, suitably scaled up with appropriate diversity, to the district, city or region scale and would therefore be useful for power network operators needing to assess the capacity of infrastructure to meet the demands of buildings.

7. Conclusion

Calculating overheating risks due to probabilistic projections of future climates through empirical regression formulae based on a single simulated climate can achieve very similar results to those of detailed simulations of many different climates. A validated tool that converts the building performance results from a single weather file into multiple climate results has been developed. It gives satisfactory results for different building types, with about 80% of hourly temperatures being within ±1°C of the simulated values, based upon over 20000 annual simulation results. A prototype user interface gives efficient use and delivers outputs that describe the results in terms of probability of failure, either as a risk matrix or a probabilistic overheating tool.

8. Acknowledgements

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Statewide Emissions Reduction, Electricity and Demand Savings from the Implementation of Building-Energy-Codes in Texas

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ABSTRACT

This paper presents estimates of the statewide emissions reduction, electricity and electric demand savings achieved in 2002-2009, the first eight years following the adoption of building-energy-codes in new construction in Texas. The paper focuses on the estimates of the electricity and electric demand savings from the adoption of energy codes for single-family residences in Texas, as well as the corresponding increase in construction costs over the eight-year period from 2002 through 2009, and the estimates of the statewide emissions reduction.

Using the Energy Systems Laboratory's International Code Compliance Calculator (IC3) simulation tool, the cumulative statewide electricity and electric demand savings over the eight year period from 2002 to 2009 are $1,706 million for the summer ($776 million from electricity savings and $929 million from demand savings) and $1,803 million for the winter periods ($776 million from electricity savings and $1,027 million from demand savings), while the total increased costs of construction are estimated to be $670 million.

In 2009, the estimated Ozone Season Day (OSD) NOx emissions reduction from energy code-compliant single-family residential construction in Texas was 4.8 tons-NOx/day. This accounts for 11.1% of the estimated total NOx emissions reduction from all of the energy efficiency and renewable energy (EE/RE) programs of the Texas Emissions Reduction Plan (TERP) that focus on stationary sources of emissions. In 2009, the annual NOx emissions reduction from energy-code-compliant residential construction built since 2002 was 879 tons-NOx/year, which is 5.7% of the estimated annual total NOx savings achieved from all of the EE/RE stationary programs of the Texas Emissions Reduction Plan. This annual amount of emissions reduced from energy-code-compliant residential construction is equal to removing NOx emissions from about 46,000 cars for an entire year.

INTRODUCTION

In 2001, the Texas Emissions Reduction Plan (TERP) was established by the 77th Texas Legislature through the enactment of Senate Bill (SB) 5. The Plan was devised to provide the Texas Natural Resource Conservation Commission – later renamed as the Texas Commission on Environmental Quality (TCEQ) – with tools that will help achieve important environmental and economic goals, which include making the air in Texas safer to breathe and meeting the minimum federal ambient air quality standards.

One of the TERP's energy efficiency programs to reduce emissions from stationary sources was the establishment of the Texas Building Energy Performance Standards (TBEPS) that define the building energy codes for all new residential and commercial construction statewide. The original TBEPS were based on the energy efficiency chapter of the 2000 International Residential Code (IRC), including the 2001 Supplement, for single-family residences, (i.e., one- and two-family residences of three stories or less above grade) and the 2000 International Energy Conservation Code (IECC), including the 2001 Supplement, for commercial, industrial and residential buildings over three stories. Over the years since the establishment of the TERP, newer editions of the IRC and the IECC have been published. The Energy Systems Laboratory has reviewed the stringency of the new code editions and provided recommendations to the State on whether to upgrade the TBEPS to the new editions. In the time frame of 2002-2009, the State of Texas did not adopt any of the newer editions of the energy efficiency codes as the TBEPS. During this timeframe, several individual jurisdictions did adopt the newer editions of the IRC and the IECC.

The analysis shows that the building energy code has substantially improved the energy efficiency of housing in Texas, resulting in reduced annual heating/cooling, which is reflected in the reduced utility bills for residential customers, reduced demand on Texas' electric grid, and reduced emissions at the power plants. This paper presents an analysis of the statewide emissions reduction resulted from the implementation of the TBEPS in single-family residential construction during the period 2002-2009, the first eight years following the initiation of the TERP, and the statewide electricity and electric demand savings achieved, including corresponding construction cost increases over the eight-year period.

METHODOLOGY

Building-Level Analysis

At the building-level analysis, the energy savings and peak demand reductions per house were calculated using the IC3 simulation program (BDL version 4.01.07 of IC3), which is based on the DOE-2.1e simulation program and the appropriate TMY2 weather files for the corresponding location. The IC3 uses a performance method of compliance.[1]

To perform the analysis, counties in Texas representing three 2006 IECC Climate Zones across Texas were selected: Harris County for Climate Zone 2, Tarrant County for Climate Zone 3, and Potter County for Climate Zone 4 (Figure 1.). For each representative county, a total of six simulations that represent pre-code 1999 conditions and code-compliant conditions meeting the requirements of the 2001 IECC and the 2006 IECC were simulated for the appropriate periods: three runs for (a) an electric/gas house (i.e., a gas-fired furnace for space heating, and a gas-fired water heater for domestic water heating) and the next three runs for (b) a heat pump house[2] (i.e., a house with a heat pump for space heating, and electric water heater for domestic water heating). Using these models, the energy savings and peak demand reductions per house compared to the pre-code building were calculated for each climate zone.

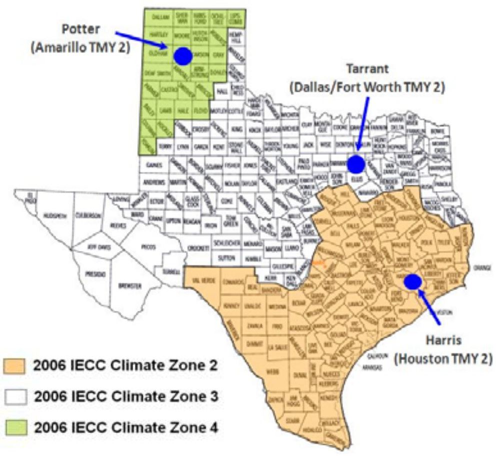

Figure 1. 2006 IECC Climate Zone Classification and Three Selected Counties in Texas

State-Level Analysis

At the state-level analysis, two different approaches were applied to calculate the statewide annual electricity and electric demand savings associated with the energy codes implementation in Texas. To calculate the statewide electricity savings in 2002-2009 from code-compliant, new single-family housing in Texas, the annual MWh savings, reported in the Laboratory's Annual Reports submitted to the TCEQ, were used (Haberl et al. 2002-2010). For the years 2002 through 2004, the annual electricity savings (MWh/year) were calculated for the 41 non-attainment and affected counties. From 2005 to 2009, the savings were calculated for all the counties in Electric Reliability Council of Texas (ERCOT) region, which includes the 41 non-attainment and affected counties. These annual electricity savings were then multiplied by the annual average electric prices in Texas published by the US DOE EIA (2011) shown in Figure 2.

To compute the statewide electric demand savings, the peak demand reductions per house calculated in the building-level analysis were multiplied by the number of new single-family houses built in each climate zone of each year (RECenter 2011) and aggregated to annual totals using an annual degradation factor of 5%. Figure 2 shows the building permits per year for new single-family residences in Texas by climate zone as well as the average statewide electricity price (¢/kWh). The ratio of electric/gas and heat pump houses constructed in Texas was determined using the annual surveys, National Association of Home Builders (NAHB) (NAHB 2001–2005 and 2009-2010). The 2001 IECC and 2006 IECC were assumed to be adopted across Texas in 2002 and 2007, respectively in the analysis. A 20% initial discount factor and a 7% transmission and distribution loss factor were applied to the calculations.

To estimate electric demand savings, the calculated statewide electric demand savings (MW) were then multiplied by the average capital cost of a natural gas combined cycle power plant, $1,165 per kW (Kaplan, 2008) using a 15% reserve margin (Faruqui et al. 2007).

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[1] The performance method of compliance is one of the two methods of compliance detailed by the IECC. The IRC, which is the prescriptive TBEPS for single-family construction, allows following the compliance requirements of the IECC.

[2] To estimate the heating savings, heat pump systems were selected for space heating of all-electric houses instead of electric-resistance heaters.

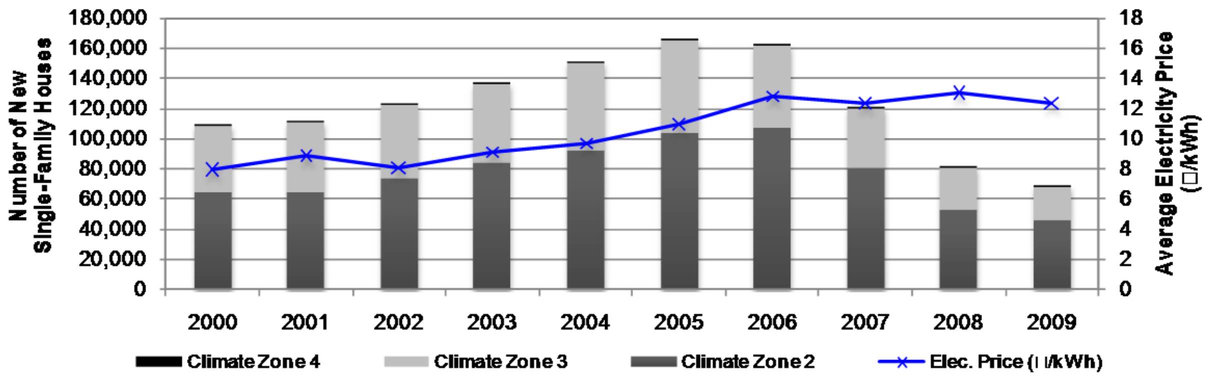


Figure 2. Number of Building Permits for New Single-Family Construction in Texas by Climate Zone and Annual Average Price of Electricity for Residential Customers in Texas

Incremental Cost Analysis

Finally, an incremental cost analysis was conducted to determine if the savings are sufficient to justify the increased construction costs for upgrading to the IECC. The increased costs for upgrading major residential building components and systems to comply with the 2001 IECC and the 2006 IECC were examined using R.S. Means Residential Cost Data (R. S. Means 2002 and 2007), the Building Codes Assistance Project (BCAP) Incremental Construction Cost Analysis for New Homes (Paquette et al. 2010), the American Council for an Energy-Efficient Economy (ACEEE) Consumer Guide to Home Energy Savings (Amann et al. 2007), and the similar incremental cost analysis studies in Texas (Malhotra et al. 2008; Kim et al. 2010). The construction characteristics published by the NAHB (2000) were used to define pre-code house conditions. The calculated per-house costs of implementation of the IECC were then multiplied by the number of new single-family houses in the ERCOT region (41 non-attainment and affected counties from 2002 to 2004 and all the counties in the ERCOT region from 2005 to 2009) and aggregated to cumulative total increased costs over the eight year period from 2002 to 2009. The 2001 IECC and 2006 IECC were assumed to be adopted across Texas in 2002 and 2007 for new single-family residences, respectively.

Annual and Ozone Season Day (OSD) Emissions Reduction Calculations

The statewide NOx emissions reductions from the electricity reductions achieved by implementing the building-energy-codes in new construction in Texas were calculated based on the US EPA's Emissions and Generation Resource Integrated Database (eGrid) for Texas[3] for both annual and Ozone Season Day (OSD) periods. For an annual estimation, the total MWh electricity savings were calculated for each Power Control Authorities (PCA) and input in the eGrid to calculate the annual emissions reduction for the corresponding PCA. The calculated NOx emissions savings for each PCA were then aggregated to compute the statewide annual NOx emissions reductions. For an OSD estimation, the daily average of the OSD period electricity savings calculated for each PCA were input in the eGrid, which were then aggregated to compute the statewide OSD NOx emissions reductions.

BASE-CASE BUILDING DESCRIPTION

The base-case building used for a simulation in the building-level analysis is a 2,325 sq. ft., square-shape, one story, single-family, detached house with a floor-to-ceiling height of 8 feet. The house has an attic with a roof pitched at 23 degrees. The wall construction is light-weight wood frame with 2x4 studs at 16" on center with a slab-on-grade-floor, which is typical construction according to the NAHB survey (NAHB 2003). The pre-code building envelope and system characteristics were determined based on the construction characteristics published by the NAHB (2000) for typical residential construction in East and West Texas for 1999. The code-compliant building envelope and system characteristics were determined from the general characteristics and the climate-specific characteristics as specified in the 2001 IECC and the 2006 IECC. Table 1 summarizes the base-case building characteristics used in the simulation model for each climate zone.

To facilitate a more accurate and realistic comparison between the codes, several modifications were applied to the simulations as follows[4]. For the

[3] The emissions savings were calculated using the 2007 eGRID database which was specially prepared for Texas by Mr. Art Diem at the US EPA using a 1999 base year.

[4] These unifying modifications to the simulation inputs were necessary because the comparisons between the pre-code, 2001 and 2006 simulations could not be performed if different values were used.

Table 1. Base Case Building Description

Characteristics	Pre-Code 1999			2001 IECC			2006 IECC		
	CZ 2	CZ 3	CZ 4	CZ 2	CZ 3	CZ 4	CZ 2	CZ 3	CZ 4
	Harris	Tarrant	Potter	Harris	Tarrant	Potter	Harris	Tarrant	Potter
Building									
Building Type	Single family, detached house								
Gross Area[2]	2,325 sq. ft. (48.21 ft. x 48.21 ft.)								
Number of Floors	1								
Floor to Floor Height (ft.)[2]	8								
Orientation	South facing								
Construction									
Construction	Light-weight wood frame with 2x4 studs spaced at 16" on center								
Floor	Slab-on-grade floor								
Roof Configuration	Unconditioned, vented attic								
Roof Absorptance	0.75								
Ceiling Insulation (hr-sq.ft.-°F/Btu)[1]	R-27.08	R-26.75		R-30	R-38		R-27.84		R-32.51
Wall Absorptance	0.75 (Assuming brick facia exterior)								
Wall Insulation (hr-sq.ft.-°F/Btu)[1]	R-13.99	R-14.18		R-11		R-12/3 c.i.	R-11.8		
Slab Perimeter Insulation	None		R-6	None		R-6	None		R-10
Ground Reflectance	0.24 (Assuming grass)								
U-Factor of Glazing (Btu/hr-sq.ft.-°F)[1]	1.11	0.87		0.47		0.41	0.75	0.65	0.40
Solar Heat Gain Coefficient (SHGC)[1]	0.71	0.66		0.40		0.68	0.40		
Window Area[2]	18% of conditioned floor area								
Interior Shading	Sum 0.7 Win 0.85			Sum 0.7 Win 0.9 (Simulation adjustment[3]: Sum 0.7, Win 0.85)			Summer 0.7, Winter 0.85		
Exterior Shading	None								
Roof Radiant Barrier	No								
Slope of Roof	5:12 (= 23 degrees)								
Space Conditions									
Space Temperature Set point	72°F Heating, 75°F Cooling			68°F Heating, 78°F Cooling, 5F setback/setup			68°F Heating, 78°F Cooling		
				(Simulation adjustment[3]: Heating 72F, Cooling 75F)					
Internal Heat Gains	1.095 kW			0.88 kW (Simulation adjustment[3]: 1.095 kW)			1.095 kW (0.547 kW for lighting and 0.547 kW for equipment)		
Number of Occupants	None (Assuming internal gains include heat gain from occupants)								
Mechanical Systems									
HVAC System Type	(a) Electric/Gas House: Electric cooling (air conditioner) and natural gas heating (gas fired furnace)								
	(b) Heat Pump House: Electric cooling and heating (air conditioner with heat pump)								
HVAC System Efficiency[1]	(a) Electric/Gas House: SEER 11 AC, 0.80 AFUE			(a) Electric/Gas House: SEER 10 AC[4], 0.78 AFUE			(a) Electric/Gas House: SEER 13 AC, 0.78 AFUE		
	(b) Heat Pump House: SEER 11 AC, 6.8 HSPF			(b) Heat Pump House: SEER 10 AC[4], 6.8 HSPF			(b) Heat Pump House: SEER 13 AC, 7.7 HSPF heat		
Cooling Capacity (Btu/hr)	55,800 (= 500 sq. ft./ton)								
Heating Capacity (Btu/hr)	55,800 (= 1.0 x cooling capacity)								
DHW System Type	(a) Electric/Gas House: 40-gallon tank type gas water heater with a standing pilot light								
	(b) Heat Pump House: 50-gallon tank type electric water heater (without a pilot light)								
DHW Heater Energy Factor	(a) Electric/Gas House: 0.544						(a) Electric/Gas House: 0.594		
	(b) Heat Pump House: 0.864						(b) Heat Pump House: 0.904		
Duct Distribution System Efficiency	0.80								
Supply Air Flow (CFM/ton)	360								
Infiltration Rate (SG)	SLA= 0.00057						SLA= 0.00036		

Note:

[1] The ceiling and wall insulation, glazing specifications, and HVAC system efficiencies for the pre-code houses were determined based on the NAHB Survey for typical residential construction in East and West Texas for 1999.

[2] For a fair comparison, the pre-code house was assumed to have the same floor area, ceiling height, and window areas as the 2001 IECC code-compliant house rather than following the NAHB survey results.

[3] To facilitate a more accurate and realistic comparison between the codes, several adjustments were applied to the 2001 and 2006 IECC codes.

[4] SEER 10 was used to comply with the 2001 IECC performance path.

2001 IECC simulation, internal heat gains and interior shading fractions for winter were adjusted to match the values required in the 2006 IECC: internal heat gains: 0.547 kW/house for lighting and 0.547 kW/house for equipment; and interior shading fraction for winter: 0.85. For all simulations, the thermostat set points were also modified to match the 2009 IECC specifications of 72°F for heating and 75°F for cooling with no set-back/set-up schedule as a more realistic estimate of savings[5].

ENERGY SAVINGS AND ELECTRIC DEMAND REDUCTIONS PER HOUSE

Table 2 summarizes the results of the energy savings analysis for Harris, Tarrant, and Potter Counties, including: the annual total site energy consumption (MMBtu/year and $/year by total and fuel types), as well as energy savings associated with the IECC code adoption. Table 3 presents summer and winter peak electric demand and reductions expected from 2001 and 2006 IECC adoption.

Annual Per-House Energy Consumption

Across all counties, the pre-code houses reported the highest consumption with a total of: (a) an electric/gas house: 122.8 MMBtu/year for Harris County, 133.9 MMBtu/year for Tarrant County, and 179.1 MMBtu/year for Potter County and (b) a heat pump house: 93.1 MMBtu/year for Harris County, 94.7 MMBtu/year for Tarrant County, and 113.0 MMBtu/year for Potter County. Conversely, the 2006 IECC code-compliant house reported the lowest site energy consumption with a total of: (a) an electric/gas house: 100.6 MMBtu/year for Harris County, 112.0 MMBtu/year for Tarrant County, and 128.9 MMBtu/year for Potter County and (b) a heat pump house: 76.7 MMBtu/year for Harris County, 79.2 MMBtu/year for Tarrant County, and 87.0 MMBtu/year for Potter County.

Similar trends were observed in the estimated annual utility bill of a house using $0.11/kWh for electricity (PUCT 2010) and $0.84/therm for natural gas (Climate Zone 2) and $0.64/therm for natural gas (Climate Zone 3 and 4) for natural gas (CPS Energy 2010, Atmos Energy 2010a and 2010b). Across the counties, the pre-code houses are expected to have the highest energy bills: (a) an electric/gas house: $2,724/year for Harris County, $2,617/year for Tarrant County, and $2,679/year for Potter County and (b) a heat pump house: $3,001/year for Harris County, $3,053/year for Tarrant County, and $3,643/year for Potter County. The 2006 IECC code-compliant houses are expected to have the lowest energy bills: (a) an electric/gas house: $2,237/year for Harris County, $2,192/year for Tarrant County, and $2,145/year for Potter County and (b) a heat pump house: $2,473/year for Harris County, $2,553/year for Tarrant County, and $2,805/year for Potter County.

Annual Per-House Energy Savings from the Adoption of the 2001 and 2006 IECC

The annual energy savings associated with the 2001 and 2006 IECC were calculated compared to the pre-code cases: (a) an electric/gas house: 14.2-22.2 MMBtu/year ($231-$487/year) for Harris County, 13.7-21.9 MMBtu/year ($209-$424/year) for Tarrant County, and 31.4-50.2 MMBtu/year ($111-$533/year) for Potter County and (b) a heat pump house: 7.5-16.4 MMBtu/year ($242-$529/year) for Harris County, 7.4-15.5 MMBtu/year ($239-$500/year) for Tarrant County, and 9.7-26.0 MMBtu/year ($313-$838/year) for Potter County. The corresponding percent savings over a pre-code house are: (a) an electric/gas house: 8.5-17.9% for Harris County, 8.0-16.2% for Tarrant County, and 4.1-19.9% for Potter County[6] and (b) a heat pump house: 8.1-17.6% for Harris County, 7.8-16.4% for Tarrant County, and 8.6-23.0% for Potter County.

For an electric/gas house, the natural gas savings (MMBtu/year) achieved from 2001 IECC is larger than electricity savings. In Potter County, the savings of all three versions of IECC codes are mainly from the savings in natural gas. However, due to the difference in the unit cost of electricity and gas, the dollar savings from electricity are higher than the savings from gas, except in Potter County. In Potter County, no electricity savings were observed from 2001 IECC code adoption. From the 2006 IECC code adoption, the savings from gas and electricity are almost the same.

Per-House Peak Electric Demand Reductions from 2001 and 2006 IECC

The pre-code houses reported the highest peak summertime demand: (a) an electric/gas house: 6.7 kW for Harris County, 7.0 kW for Tarrant County, and 7.0 kW for Potter County and (b) a heat pump house: 7.1 kW for Harris County, 7.3 kW for Tarrant County, and 7.5 kW for Potter County. Not surprisingly, the 2006 IECC code-compliant house

[5] Although the results of the 2009 IECC simulations are not reported in this report, ongoing work identified these changes to the simulation inputs.

[6] A negative electricity savings was expected for a 2001 IECC code-compliant, electric/gas house in Potter County due to the increased cooling energy consumption. This is because a lower SEER (SEER 10) A/C unit was used for a 2001 IECC code-compliant house simulation to comply with the 2001 IECC performance path requirement. For a pre-code house, a SEER 11 A/C unit was used from the NAHB survey results (2000).

Table 2. Annual Per-House Energy Savings from IECC Code-Compliant, Single Family Residences in Texas

Test Cases		Annual Total Site Energy Consumption						Annual Total Site Energy Savings						
		(MMBtu/year)			($/year)			(MMBtu/year)			($/year)			
		Total	Elec.	NG	Total	Elec.	NG	Total	Elec.	NG	Total	Elec.	NG	% Savings vs. Pre-Code
(a) Electric/Gas House														
Harris County (CZ 2)	**Pre-Code 1999**	122.8	71.0	51.8	$2,724	$2,289	$435	-	-	-	-	-	-	-
	2001 IECC Modified	108.6	66.3	42.3	$2,493	$2,137	$355	14.2	4.7	9.5	$231	$152	$80	**8.5%**
	2006 IECC Modified	100.6	58.4	42.2	$2,237	$1,883	$354	22.2	12.6	9.6	$487	$406	$81	**17.9%**
Tarrant County (CZ 3)	**Pre-Code 1999**	133.9	68.1	65.8	$2,617	$2,195	$421	-	-	-	-	-	-	-
	2001 IECC Modified	120.2	63.4	56.8	$2,407	$2,044	$364	13.7	4.7	9.0	$209	$152	$58	**8.0%**
	2006 IECC Modified	112.0	57.1	54.9	$2,192	$1,841	$351	21.9	11.0	10.9	$424	$355	$70	**16.2%**
Potter County (CZ4)	**Pre-Code 1999**	179.1	59.3	119.8	$2,679	$1,912	$767	-	-	-	-	-	-	-
	2001 IECC Modified	147.7	62.8	84.9	$2,568	$2,025	$543	31.4	-3.5	34.9	$111	-$113	$223	**4.1%**
	2006 IECC Modified	128.9	51.1	77.8	$2,145	$1,647	$498	50.2	8.2	42.0	$533	$264	$269	**19.9%**
(b) Heat Pump House														
Harris County (CZ 2)	**Pre-Code 1999**	93.1	93.1	-	$3,001	$3,001	-	-	-	-	-	-	-	-
	2001 IECC Modified	85.6	85.6	-	$2,760	$2,760	-	7.5	7.5	-	$242	$242	-	**8.1%**
	2006 IECC Modified	76.7	76.7	-	$2,473	$2,473	-	16.4	16.4	-	$529	$529	-	**17.6%**
Tarrant County (CZ 3)	**Pre-Code 1999**	94.7	94.7	-	$3,053	$3,053	-	-	-	-	-	-	-	-
	2001 IECC Modified	87.3	87.3	-	$2,814	$2,814	-	7.4	7.4	-	$239	$239	-	**7.8%**
	2006 IECC Modified	79.2	79.2	-	$2,553	$2,553	-	15.5	15.5	-	$500	$500	-	**16.4%**
Potter County (CZ4)	**Pre-Code 1999**	113.0	113.0	-	$3,643	$3,643	-	-	-	-	-	-	-	-
	2001 IECC Modified	103.3	103.3	-	$3,330	$3,330	-	9.7	9.7	-	$313	$313	-	**8.6%**
	2006 IECC Modified	87.0	87.0	-	$2,805	$2,805	-	26.0	26.0	-	$838	$838	-	**23.0%**

Table 3. Annual Per-House Peak Electric Demand Reductions from IECC Code-Compliant, Single Family Residences in Texas

Test Cases		Summer Demand (kW)			Winter Demand (kW)		
		Peak Demand[1]	Reduction	% Reduction vs. Pre-Code	Peak Demand[2]	Reduction	% Reduction vs. Pre-Code
(a) Electric/Gas House							
Harris County (CZ 2)	**Pre-Code 1999**	6.7	-	-	-	-	-
	2001 IECC Modified	6.2	0.5	8.1%	-	-	-
	2006 IECC Modified	4.8	2.0	29.5%	-	-	-
Tarrant County (CZ 3)	**Pre-Code 1999**	7.0	-	-	-	-	-
	2001 IECC Modified	6.4	0.6	8.4%	-	-	-
	2006 IECC Modified	5.1	1.9	27.2%	-	-	-
Potter County (CZ4)	**Pre-Code 1999**	7.0	-	-	-	-	-
	2001 IECC Modified	7.0	0.0	0.0%	-	-	-
	2006 IECC Modified	5.1	1.9	27.1%	-	-	-
(b) Heat Pump House							
Harris County (CZ 2)	**Pre-Code 1999**	7.1	-	-	11.3	-	-
	2001 IECC Modified	6.5	0.5	7.7%	8.2	3.1	27.6%
	2006 IECC Modified	5.1	2.0	28.4%	7.7	3.6	32.0%
Tarrant County (CZ 3)	**Pre-Code 1999**	7.3	-	-	12.0	-	-
	2001 IECC Modified	6.7	0.6	8.1%	9.6	2.4	19.6%
	2006 IECC Modified	5.4	1.9	26.3%	8.5	3.5	29.5%
Potter County (CZ4)	**Pre-Code 1999**	7.5	-	-	17.9	-	-
	2001 IECC Modified	7.5	0.0	0.0%	13.8	4.0	22.5%
	2006 IECC Modified	5.5	1.9	25.8%	12.2	5.6	31.4%

Note:

[1]Summer Peak Demand Date: (a) Electric/Gas House-September 16 (CZ 2), August 13 (CZ 3), and June 29 (CZ 4); and (b) Heat Pump House-September 16 (CZ 2), August 13 (CZ 3), and June 29 (CZ 4)

[2]Winter Peak Demand Date: (b) Heat Pump House-January 11 (CZ 2), January 15(CZ 3), and January 7 (CZ 4)

reported the lowest peak summertime demand: (a) an electric/gas house: 4.8 kW for Harris County, 5.1 kW for Tarrant County, and 5.1 kW for Potter County and (b) a heat pump house: 5.1 kW for Harris County, 5.4 kW for Tarrant County, and 5.5 kW for Potter County. In the analysis, the same peak day was used regardless of the house type: September 16 for Harris County, August 13 for Tarrant County, and June 29 for Potter County.

In the winter, the peak electric demands were estimated for a heat pump house. The peak days used in the analysis were: January 11 for Harris County, January 15 for Tarrant County, and January 7 for Potter County. As reported, the highest peak wintertime electric demands are for a pre-code house: 11.3 kW for Harris County, 12.0 kW for Tarrant County, and 17.9 kW for Potter County. The lowest wintertime demands for the 2006 IECC code-compliant house are: 7.7 kW for Harris County, 8.5 kW for Tarrant County, and 12.2 kW for Potter County.

Finally, the peak electric demand reductions associated with the 2001 and 2006 IECC were calculated for both summer and winter. For summer, the reductions in peak summertime electric demands are expected to happen in the afternoon between 3 to 5 pm for both electric/gas and heat pump houses: 0.5-2.0 kW for Harris County, 0.6-1.9 kW for Tarrant County, and 1.9 kW for Potter County. In Potter County, no demand savings are expected in summer from the 2001 IECC code adoption. For winter, the electric demand reductions were estimated to occur in early morning hours between 6 and 8 am for a heat pump house: 3.1-3.6 kW for Harris County, 2.4-3.5 kW for Tarrant County, and 4.0-5.6 kW for Potter County. The corresponding percentage summer electric demand reductions over a pre-code house are: (a) an electric/gas house: 8.1-29.5% for Harris County, 8.4-27.2% for Tarrant County, and 27.1% for Potter County and (b) a heat pump house: 7.7-28.4% for Harris County, 8.1-26.3% for Tarrant County, and 25.8% for Potter County. In winter, the percent reductions are: (b) a heat pump house: 27.6-32.0% for Harris County, 19.6-29.5% for Tarrant County, and 22.5-31.4% for Potter County.

INCREMENTAL COST ANALYSIS

The per-house increased costs for upgrading major building components and systems to comply with the 2001 IECC and the 2006 IECC were estimated for each climate zone[7]. As a result, the per-house increased construction costs for upgrading to the 2001 IECC are estimated to be $600 for Climate Zone 2, $778 for Climate Zone 3, and $1,215 for Climate Zone 4. To comply with the 2006 IECC, the per-house increased costs are estimated to be $1,002 and $ 902 for Climate Zone 2, $1,015 and $1,115 for Climate Zone 3, and $1,644 and $1,744 for Climate Zone 4 for the electric/gas and heat pump houses, respectively.

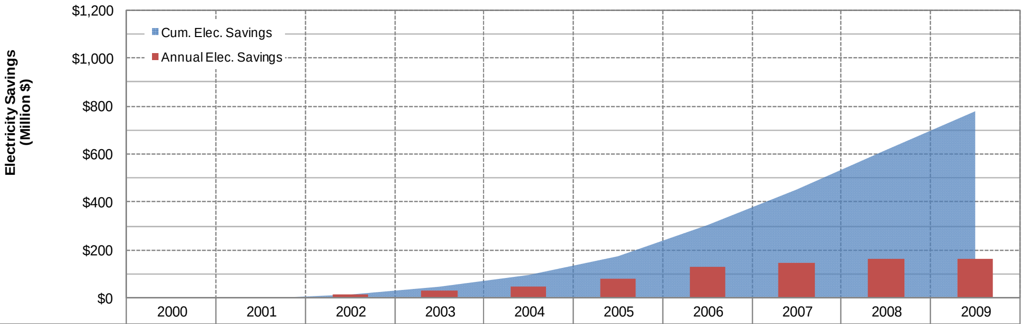
STATEWIDE ELECTRICITY AND ELECTRIC DEMAND SAVINGS

Figure 3 presents the annual and cumulative statewide electricity savings from code-compliant new single-family housing in Texas for years 2002 through 2009. Figure 4 presents the summer and winter electric demand reductions and the corresponding electric demand savings. The annual statewide electricity savings in 2009 are estimated to be $161 million, and the total cumulative electricity savings over the period from 2002 to 2009 are estimated to be $776 million. Although expected MWh savings in 2009 (1,301,063 MWh) are higher than 2008 MWh savings (1,256,764 MWh), a decrease of dollar savings in 2009 is expected because of lower electricity rates in 2009: from $0.13/kWh to $0.12/kWh. The electric demand reductions in 2009 are estimated to be 694 MW for the summer and 766 MW for the winter periods. The corresponding electric demand savings from the reduced peak demands (i.e., avoided construction cost of a peaking plant) are estimated to be $929 million for the summer and $1,027 million for the winter periods from 2002 to 2009.

Figure 5 shows the cumulative statewide increased costs with the cumulative statewide electricity and demand savings from code-compliant, single-family residences built between 2002 and 2009.[8] The cumulative statewide costs over the eight year period from 2002 to 2009 are estimated to be $670 million while the cumulative electricity and demand savings are $1,706 million for the summer ($776 million from electricity savings and $929 million from demand savings) and $1,803 million for the winter periods ($776 million from electricity savings and $1,027 million from demand savings).

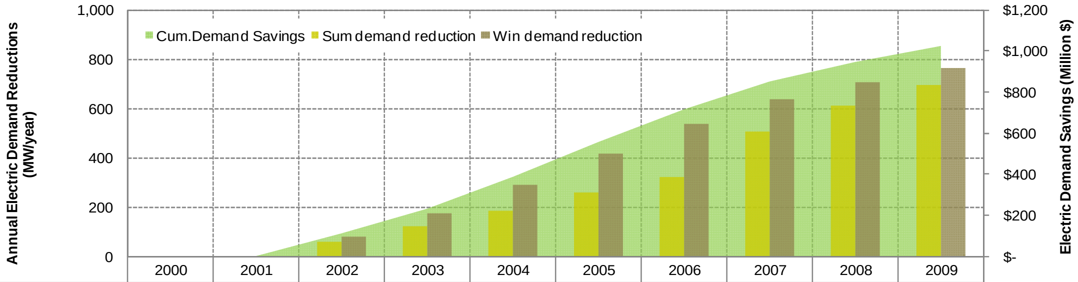
[7] Details on the results of incremental cost analysis are available in Kim et al. (2011).

[8] In the figure, for electric demand savings, the estimation for the winter periods ($1,027 million, cumulative) was displayed instead of summer ($929 million, cumulative).



	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009
Cum. Elec. Savings	-	-	$16	$48	$97	$175	$304	$451	$615	$776
Annual Elec. Savings	-	-	$16	$32	$49	$78	$129	$148	$164	$161

Figure 3. Annual and Cumulative Statewide Electricity Savings from the IECC Code Adoption for New Single-Family Residences in Texas: 2002-2009



	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009
Cum.Demand Savings	-	-	$111	$232	$387	$558	$717	$853	$949	$1,027
Sum demand reduction	-	-	59	121	188	257	321	506	614	694
Win demand reduction	-	-	83	173	289	417	535	637	708	766

Figure 4. Annual Statewide Electric Demand Reductions and Electric Demand Savings from the IECC Code Adoption for New Single-Family Residences in Texas: 2002-2009

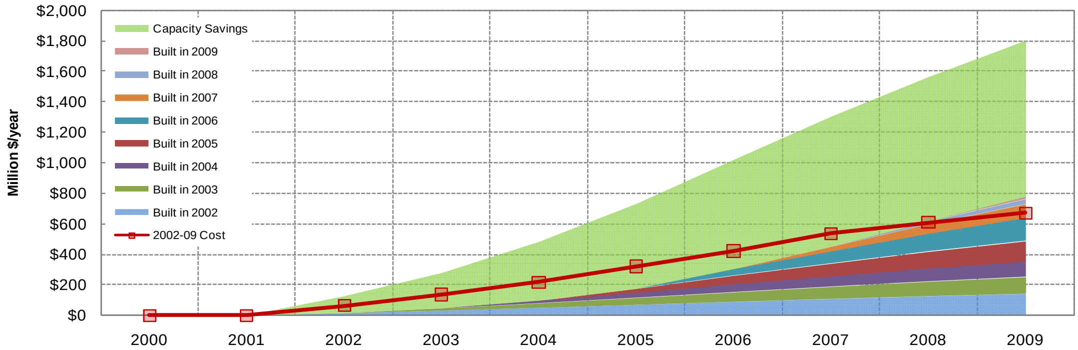


Figure 5. Cumulative Increased Costs, Statewide Electricity and Electric Demand Savings Associated with the IECC Code Adoption for Single-Family Residences in Texas: 2002-2009

Table 4. The total annual and OSD emissions reduction from energy code-compliant single-family construction in Texas and other EE/RE stationary programs under TERP, 2002-2009.

Year	Annual Emissions Reduction (tons NOx/yr)			# of cars taken off the road for 1 year equivalent to the annual emissions reduction from energy code-compliant single-family residential construction in Texas[1]	Ozone Season Day (OSD) Emissions Reduction (tons-NOx/day)		
	Energy code-compliant single-family residential construction in Texas	All EE/RE programs under TERP for stationary emissions sources[2]	% of code-compliant single-family residential construction out of stationary EE/RE programs under TERP		Energy code-compliant single-family residential construction in Texas	All EE/RE programs under TERP for stationary emissions sources	% of code-compliant single-family residential construction out of stationary EE/RE programs under TERP
2002							
2003	340	473	71.9%	17,801	2.13	2.44	87.3%
2004	301.67	346	87.2%	15,794	1.77	1.89	93.7%
2005	157.64	3,119	5.1%	8,253	0.76	8.09	9.4%
2006	707.64	6,760	10.5%	37,049	3.85	19.53	19.7%
2007	842.66	8,839	9.5%	44,118	4.50	26.24	17.1%
2008	883.34	12,727	6.9%	46,248	4.76	31.38	15.2%
2009	879.27	15,327	5.7%	46,035	4.81	43.28	11.1%
Total 2002-2009	**4112.22**	**47,591**	**8.6%**	**215,299**	**22.58**	**132.85**	**17.0%**

Note:

[1] Based on 38.2 lbs-NOx/car per year, from 2000 EPA web page

[2] TERP EE/RE programs for stationary emissions sources include: code-complaint construction, Federal buildings, the Texas Public Utility Commission (PUC) Senate Bill 7 and Senate Bill 5 programs, the EE programs managed by the Texas State Energy Conservation Office (SECO), electricity generated from wind power, and several additional statewide measures, including SEER 13 air conditioner and pilot lights.

ANNUAL AND OZONE SEASON DAY (OSD) EMISSIONS REDUCTION

Table 4 presents the annual (tons-NOx/yr) and OSD (tons-NOx/day) emissions reduction from energy code-compliant single-family construction in Texas and from all other EE/RE stationary programs under TERP.[9] The cumulative annual and OSD emissions reductions from 2002 to 2009 were also aggregated and presented in the last row of the table.

In 2009, the estimated annual NOx emissions reduction from energy code-compliant single-family residential construction in Texas was 879 tons-NOx/yr. This accounts for 5.7% of the estimated total NOx emissions reduction from all of the TERP EE/RE stationary programs, which was 15,327 tons-NOx/yr. This amount of emissions reduced from energy-code-compliant residential construction is equal to removing NOx emissions from about 46,000 cars for an entire year.

The cumulative annual NOx emissions reduction from energy-code-compliant residential construction from 2002 to 2009 was 4,112 tons-NOx/year, which is 8.6% of 47,591 tons-NOx/year - the estimated total NOx savings achieved from all of the TERP EE/RE stationary programs. This amount of emissions reduced from energy-code-compliant residential construction is equal to removing NOx emissions from about 215,300 cars for one full year over the 2002 to 2009 period.

In 2009, the estimated OSD NOx emissions reduction from energy code-compliant single-family residential construction in Texas was 4.8 tons-NOx/day. This accounts for 11.1% of the estimated total NOx emissions reduction from all of the TERP EE/RE stationary programs, which was 43.3 tons-NOx/day.

The cumulative OSD NOx emissions reduction from energy-code-compliant residential construction from 2002 to 2009 was 22.6 tons-NOx/year, which is 17.0% of 132.9 tons-NOx/year - the estimated total OSD NOx savings achieved from all of the TERP EE/RE stationary programs.

It is interesting to note that the percentage of emissions reduced that is attributed to energy-code-compliant residential construction out of all the TERP EE/RE stationary programs is greater for OSD calculations than in the annual estimation. This can be attributed to the summertime reduction in air-conditioning savings and the reduction in wind power generation, which is one of the largest emission reducing TERP EE/RE stationary programs.

[9] Details on the various TERP EE/RE stationary programs are available in Baltazar et al. 2010.

SUMMARY

Statewide emissions reduction, electricity savings and peak electric demand reductions achieved from energy code adoption for single-family residences in Texas and the corresponding increase in construction costs over the eight-year period from 2002 through 2009 are presented in this paper. In the first part of the analysis, the impact of different versions of the code (2001 and 2006) on energy savings and peak demand reductions were calculated at the individual building level using the ESL's IC3 simulation tool based on the DOE-2.1e program for three counties in Texas.

To calculate the electricity cost savings at the statewide level, the annual MWh savings from code-compliant new single-family housing in Texas for years 2002 through 2009 which were reported in the Laboratory's Annual Reports to the TCEQ, were tabulated and multiplied by the annual average prices of Texas residential electricity published by the U.S. DOE EIA. To compute the statewide annual electric demand reductions, the peak demand reductions per house calculated in the building-level analysis were multiplied by the number of new single-family houses built in each climate zone of each year, and aggregated to annual totals with an annual degradation factor of 5%. To compute the avoided construction cost of a peaking plant (i.e., electric capacity savings), the calculated statewide electric demand savings in MW were multiplied by the average capital cost of a natural gas combined-cycle power plant, $1,165 per kW, with a 15% reserve margin. The statewide NOx emissions reductions were calculated based on the US EPA's Emissions and Generation Resource Integrated Database (eGrid) for Texas. For an annual estimation, the total MWh electricity savings were calculated for each Power Control Authorities (PCA) and input in the eGrid to calculate the annual emissions reduction for the corresponding PCA. The calculated NOx emissions savings for each PCA were then aggregated to compute the statewide annual NOx emissions reductions. For an Ozone Season Day (OSD) estimation, the daily average of the OSD period electricity savings calculated for each PCA were input in the eGrid, which were then aggregated to compute the statewide OSD NOx emissions reductions.

As a result, the annual statewide electricity savings in 2009 are estimated to be $161 million, and the statewide electric demand reductions in 2009 are estimated to be 694 MW for the summer and 766 MW for the winter periods. Finally, the cumulative statewide electricity and electric capacity savings from the electric demand savings over the eight year period from 2002 to 2009 are estimated to be $1,803 million ($776 million from electricity savings and $1,027 million from capacity savings), which exceeds the increased construction costs estimated to be $670 million.

In 2009, the estimated OSD NOx emissions reduction from energy code-compliant single-family residential construction in Texas was 4.8 tons-NOx/day. This accounts for 11.1% of the estimated total NOx emissions reduction from all of the energy efficiency and renewable energy (EE/RE) programs of the Texas Emissions Reduction Plan that focus on stationary sources of emissions. In 2009, the annual NOx emissions reduction from energy-code-compliant residential construction built since 2002 was 879 tons-NOx/year, which is 5.7% of the estimated annual total NOx savings achieved from all of the EE/RE stationary programs of the Texas Emissions Reduction Plan. This annual amount of emissions reduced in 2009 from energy-code-compliant residential construction is equal to removing NOx emissions from about 46,000 cars for an entire year. The cumulative NOx emissions reduction in the years 2002-2009 combined, achieved from energy-code-compliant residential construction, is 4,112 tons-NOx. This amount of emissions is equal to removing NOx emissions from about 215,300 cars for an entire year.

ACKNOWLEDGEMENT

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NABERS: Lessons from 12 Years of Performance Based Ratings in Australia

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Abstract:
The National Australian Built Environment Rating System (NABERS) has been operating for 12 years as a performance based rating system for the energy/greenhouse efficiency of office buildings in Australia. During this period, the scheme has been expanded to include performance based energy and water ratings for offices, hotels and shopping centres, plus performance based rating tools for office indoor environment and waste.

NABERS has achieved significant success in transforming the energy efficiency of the office building stock, particularly with respect to the landlord operated services in the higher-quality end of the market. NABERS ratings have become established as a core valuation in the market for sale or lease of these buildings. The declaration of NABERS ratings has recently become mandatory for commercial sale and lease transactions over 2000m².

In this paper, the history of the NABERS scheme is outlined, with particular emphasis on the key lessons learnt and the underlying factors that have contributed to successes and failures along the way. Directions for future development are also discussed.

Keywords:
Efficiency, Energy, Performance, Rating, Water, Market Transformation.

1. Introduction

Rating systems are a means of communicating a complex technical message in a format readily understood by the non-technical market. Ideally, this enables decision makers (who are typically financially rather than engineering trained) to factor efficiency into commercial decisions.

The development of such rating systems has occurred in a piecemeal manner internationally. Early adopters include Australia (NABERS, 2012a) and USA (Energy Star) (US EPA, 2012), both of which started operation in the late 1990s. In Europe, significant development of rating systems has occurred subsequent to the European Building Performance Directive (EU 2002). In addition, a wide range of design-based sustainability tools incorporating energy as one component has developed over the past 15 years, led by LEED (US GBC 2012), BREEAM (BRE, 2012) and Green Star (GBCA, 2012).

This paper presents the history and associated insights related to the development of the National Australian Built Environment Rating Scheme (NABERS).

2. NABERS Development History

The original development of NABERS dates from 1998 when the Sustainable Energy Development Authority of NSW called for tenders to develop a building energy/greenhouse efficiency rating scheme. The original scope was relatively non-specific as to the nature of the rating, other than that it should provide a means of differentiating buildings of different efficiency levels.

Over 1998-9 a development process was conducted to determine the detail of the rating system. Originally, significant development was put towards the development of both a performance rating system (based on energy bills) and a design based system (based on design potential). However, the latter component was dropped as being too complex and unproven in its ability to generate actual greenhouse reductions, resulting ultimately in the release of the Australian Building Greenhouse Rating (ABGR) for NSW in September 1999.

Although the rating was notionally national in coverage, the other state jurisdictions generally did not accept ABGR to begin with, with the largest concern being whether the rating benchmarks were appropriate for each individual state. This was not an unreasonable concern, as the original dataset was of variable quality and biased towards NSW. The state of Victoria adopted ABGR in 2000 but only after conducting its own benchmarking exercise and negotiating changes to the operation of the scheme – specifically the conversion of the rating from using gross conditioned area to net lettable area and the addition of half stars to the rating; both of these were sensible changes to the scheme that facilitated its wider acceptance in the market.

Other states followed with separate benchmarking exercises (Western Australia, followed by Queensland) albeit with no further operational changes to the scheme. Benchmarks for the Northern Territory were modified in 2006 to reflect issues with the rating in tropical climates (the rating tended to over-rate buildings in the tropics). A further update to the Victorian benchmarks was applied in 2010 to respond to industry criticism that the benchmark was perceived as being set "harder" in that state than in NSW. South Australia, New South Wales and the Australian Capital Territory all use the original benchmarks developed in 1999, adjusted for the change in area assessment from 2000.

The concept of performance-based assessment had received a significant amount of interest within the Australian (Federal) government and in 2005 this was pursued with the development of a conceptual performance based rating scheme covering wide-based sustainability issues such as indoor air quality, waste, transport, water and energy. This scheme was called the National Australian Built Environment Rating Scheme (NABERS). The scheme was developed to a moderate level of detail and its operation was awarded on tender to the NSW Government team running NABERS (by that stage being the NSW Department of Energy Utilities and Sustainability), who also undertook to develop the rating to a full-release level.

As part of this work, a performance based water benchmark was developed for offices, which was released as NABERS Water for Offices in 2006. This was particularly timely as Australia was in the midst of a ten year drought and urban water consumption was a major issue. NABERS Indoor Environment and Waste ratings for offices were subsequently released, both also following the performance-based ethos of the original ABGR, but with necessarily a very different approach. ABGR and NABERS were integrated in 2009, a move which reflected the fact that ABGR was already operating as the energy/greenhouse benchmark for NABERS; after the merger, ABGR became known as NABERS Energy for Offices. NABERS Energy and Water ratings for Homes were also developed in this period following a similar methodology.

In the period 2008-2009, further development work was undertaken to create performance based benchmarking systems for business hotels and shopping centres, subsequently released as NABERS Energy/Water for Shopping Centres and NABERS Energy/Water for Hotels.

To this point, NABERS had been an entirely voluntary system, with a voluntary uptake on approximately 60% of Australian office's net lettable area. . However, in November 2010 the declaration of NABERS ratings became mandatory for commercial office sale and lease transactions over 2000m², under the Building Energy Efficiency Disclosure Act 2010.

In 2011, the rating scale was expanded from its original 5 stars to 6 stars, reflecting the growth of a significant sector of the market outperforming what had originally been set as an aspirational limit in 1999; 6 stars was set at 50% of the greenhouse emissions of 5 stars, thereby pointing to a notional 7 star/ zero-emissions rating in the future.

3. NABERS – Key Structural Elements

3.1. Common Elements

The various NABERS Energy and Water ratings, which are the primary focus of this paper, share a common structure including a number of key elements:

- The ratings are based on actual consumption
- Corrections are made for unavoidable operational factors (e.g. hours of occupancy, climate) but not for efficiency related factors (plant, building envelope, age)
- The rating scale is based on a median building achieving a rating of approximately 2.5 stars, and an aspirational building achieving 5 stars. The minimum rating is 1 star; ratings of less than this are not certificated. As of 2011, the scale has been extended for all Energy and Water ratings (other than NABERS Homes) to include 6 stars at 50% of the emissions or water consumption of 5 stars. Half star ratings are awarded from 1.5 stars to 5.5 stars.
- The rating scale is bi-linear, with one slope from 1-5 stars and a different slope from 5 stars and above.
- Energy ratings are based on greenhouse emissions calculated from actual energy consumption. As emissions factors are significantly different from state to state, the positioning of the median is adjusted to compensate for this. As a result, the 2.5-3 star median holds true in each state individually, rather than states with greenhouse-intensive generators uniformly rating badly.

3.2. Offices Energy Ratings

Office energy ratings are divided into three categories:

- Base building ratings: Covering the services generally under the control of the landlord, being primary air-conditioning, lifts, common area lighting, and car parks.

- Tenancy ratings: Covering the services generally under the control of the tenant, being lighting within the tenancy, tenant equipment (i.e. computers etc) and supplementary tenant air-conditioning (i.e. for meeting rooms).
- Whole building ratings: Covering all base building and tenancy services.

These divisions reflect relatively common metering boundaries for building in Australia. The presence of this split in energy data, and the relative consistency of metering boundaries in the field, has played a central role in the success of the offices energy rating. This is because the base building rating provides a rating which is largely independent of tenant energy efficiency performance, and thus enables the advertisement of the building's performance in a manner that is largely independent of the current tenant profile. The metering boundaries are well aligned with control of energy using services, and well aligned with the office leasing market. This has been critical in creating the market transformation drivers discussed in Section 4.2.

The operational factors corrected for in office energy ratings are:

- Base buildings: Climate (indexed by postcode across approximately 80 climate zones), requested hours of service and net lettable floor area.
- Tenancies: Hours of occupancy, number of computers (as an index of general equipment density) and net lettable floor area.
- Whole buildings: Climate, hours of occupancy, number of computers (as an index of general equipment density) and net lettable floor area.

An approximate idea of the rating scale stringency within temperate mainland states is as follows, based on a building utilizing 80% electricity and 20% gas:

- For whole buildings: 2.5 stars threshold 996-1251MJ/m²; 5 stars threshold 544-592MJ/m².
- For base buildings: 2.5 stars threshold 545-685MJ/m²; 5 stars threshold 314-331MJ/m².

Across all states the 5 star threshold is typically 43-60% (base building) or 43-52% (whole building) of the 2.5 star threshold.

In terms of calculation, the office energy rating is structured differently from the other energy and water ratings, largely due to the age of the rating methodology itself. For the office rating the benchmarking methodology uses a normalized emissions basis for comparison of building with different operating characteristics. Under this approach, the gross emissions are calculated for the building and then corrected for operational factors which have been theoretically derived to create a normalized emissions figure reflecting the expected performance of the building normalized to Sydney climate, 50 hours a week occupancy and 8W/m² (at 200W total equipment per computer) overall equipment density. This normalized emissions figure is then compared to a fixed rating scale reflecting the performance of a standardized building operating under the normalized conditions.

This calculation methodology has served well over 12 years but has limitations for high efficiency buildings, as some of the normalization factors are additive and thus a zero-emissions building outside Sydney, for instance, has non-zero normalized emissions. This issue was known at the time of the original development but was seen as being "off the horizon" as at that stage the best ratings available were at 4 stars, while this issue only arises for buildings well above 5 stars (as the normalization factors were effectively set based on a 5 star building). The 2011 update to extend the scale to 6 stars addressed this issue by fixing the gross emissions at 5 stars and calculating ratings above this as a fraction of the 5 star gross emissions.

A significant feature of the offices rating is that all of the normalization factors were derived theoretically. This to some extent reflects the limitations of the underlying dataset but also reflects the limited domain and range of such factors. Thus for instance, theoretical studies undertaken at the time of development predicted a change in gross emissions due to climate of less than 10% from Melbourne to Brisbane (a change in latitude of 10°, not allowing for differences in greenhouse emissions factors); this compares to the 200%+range of the rating scale. For hours, the dataset was generally limited to 50-70 hours per week operation. Derivation of a correction factor to extrapolate hours effects to 168 hours on this basis was not practical, so simulation estimates were used.

3.3. Offices Water Ratings

The Office Water rating is available as a whole building rating only and is normalised for climate, hours of operation and net lettable area only.

Unlike offices energy, and in common with all the other energy and water ratings, the water rating is calculated on a variable benchmark basis. Under this methodology, the median water consumption is calculated based on an equation that incorporates climate and occupancy factors, and the performance of the building is calculated based on the percentage deviation from this median. In effect this calculates the expected water consumption for a building in the location and with the hours of the sample building, and compares actual performance to that rather than trying to normalized the building itself to a standard.

Although this approach is functionally interchangeable with the normalized building method, it avoids the issues at high efficiency associated with the normalized building method.

The climate dependence of water consumption was found to be very strong, with the average water consumption in cool temperate regions (Melbourne, Adelaide, Canberra) being approximately 0.7kl/m² while in subtropical Brisbane the average consumption is 1.56kl/m²; extrapolation of these figures to cold climates aligns well with UK water consumption benchmarks (Bannister and Bloomfield 2007). As a result, the climate adjustment for the rating is based on empirical data. However for the same reasons as discussed earlier for the energy rating, a theoretical adjustment factor was derived for the hours correction.

3.4. Other NABERS Ratings

NABERS incorporates a number of additional ratings which follow the same performance based-philosophy as the offices energy and water ratings. In particular:

- Hotels: Energy and water ratings are available for business hotels. These are both based on the variable benchmark methodology but are otherwise very similar to the offices energy and water ratings. To date, 49 Energy and 53 Water ratings have been undertaken; there are 20 sites with current energy and water ratings at the time of writing.

- Shopping Centres: Energy and water ratings are available for the owners of shopping centres of greater than 15,000m². These are structured very similarly to the hotel energy and water ratings. However the energy rating is effectively a "base building" rating only as it rates the energy consumption of the owner which excludes tenancy lighting and power and also excludes a significant amount of tenant-provided air-conditioning. (Bloomfield and Bannister 2010). This results in a somewhat more complex rating, but one which is gaining recognition and use in the market place. To date, there have been 89 Energy and 85 Water ratings; there are approximately 45 sites with current energy and water ratings.
- Offices Indoor Environment. The offices indoor environment rating is based on measurement of key variables such as indoor air quality, noise and light levels. A base building rating is provided based entirely on measurements, while tenancy and whole building ratings incorporate post-occupancy evaluation surveys. Thirty one sites have undertaken Indoor Environment ratings; there are 12 current ratings at the time of writing.
- Office Waste. The offices waste measurement is based on measurement of normal office waste across a 10 working day period and provides ratings based on total waste quantity and percentage recycling. Thirty one sites have undertaken office waste ratings.

4. Market Impacts

4.1. Roll-out and Adoption

The program has grown immensely since 1999, as can be seen in Figure 1. The vast majority of ratings undertaken are office ratings, where the market penetration by floor area in 2011 has been estimated at approximately 66% for energy and 41% for water ratings (NABERS, 2012b).

In the early days of the scheme, there were relatively few ratings and these were generally conducted in a one-off manner. The level of interest increased markedly when the NSW Government nominated (appx 2002) that all NSW government leases should be in properties with a minimum rating of 3.5 stars for existing buildings and 4.5 stars for new buildings. As government is a major office tenant in Australia, this certainly engaged the attention of the upper property sector and led to much of the first phase of rating activity in the period 2002-2006.

The impact of this requirement on the market can be appreciated when it is understood that at the time the policy was released there were no 4.5 star buildings in NSW and thus no knowledge as to what would be required to build such a building. The rate of change in the market, however, was such that the requirement for *existing* buildings was reset to 4.5 stars after a period of only a few years

Rating activity was supplemented by the gradual adoption of a 4.5 star target for new and existing government leases by all states (except Tasmania) and the Australian federal government over the period 2002-2009. Mandatory disclosure of NABERS Ratings commenced in 2010.

4.2. Factors Driving Voluntary Adoption

The high level of voluntary adoption, which in turn led to the successful roll-out of mandatory adoption with remarkably little objection from industry, is a key factor in the success of NABERS. It is useful therefore to assess the factors contributing to this:

- Base Building/Tenancy Split. The ability to separately rate the base building in a manner that is largely independent of the tenants is a critical success factor for NABERS and also differentiates it from schemes such as Energy Star. In particular, the separate assessment of base buildings means that the base building rating can be used as a generic measure of efficiency in procurement i.e. it is possible to seek a base building rating without consideration of current tenant behavior and efficiency, and to expect that this rating will be able to be maintained through the duration of a new lease.

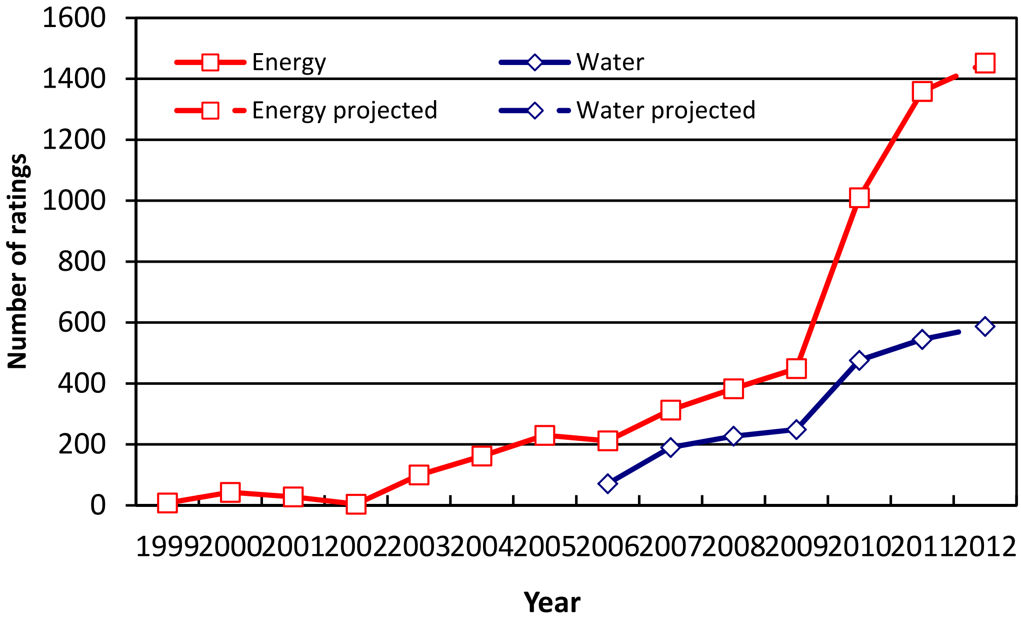

Figure 1. Number of ratings conducted. Figures from 2010 onwards include hotel and shopping centre ratings. Source: NSW Office of Environment and Heritage

- Government procurement. The incorporation of the base building rating into government procurement played an essential role in turning the rating from an object of technical interest to an object of commercial interest. This is because over a period of 5 years, the ability of higher star-rated buildings to obtain government leases (which are large, long, and low risk) has become recognized as a factor in building valuation. As a result, high NABERS ratings have increasingly become correlated with higher rents and higher capital valuations.
- Corporate sustainability. As the investor market has become more environmentally conscious, the ability of property to differentiate itself as an environmentally responsible investment option has played an increasing role in determining the NABERS aspirations of corporate and property trust portfolios. By setting and achieving strong environmental targets, Australian property funds have been able to

gain international recognition for sustainability performance, leading to increased investment.

- Core business vs efficiency. The factors above combine to move efficiency from being a technical issue to being a core business value. This changes the parameters of efficiency investment from a narrow energy-payback model to a model that considers efficiency as part of the general tenant service provision, and thus investment is driven by the prospect of improved lettability and improved rental rather than energy costs. This also has the effect of bypassing the traditional split incentives (most leases in Australia pass base building energy costs to tenants).

4.3. Industry Efficiency Improvements

All of the major property portfolios have embarked on a program of NABERS upgrades over the past 6 years. The results from these have been significant:

- Investa: Increase in average NABERS Energy Rating from 2.6 to 3.99 stars from 2003-2011; 43% reduction in portfolio emissions. Increase in average NABERS Water rating from 2.87-3.54 stars from 2005-2011; 43% reduction in portfolio water consumption intensity (Investa, 2011)
- Colonial First State (Commonwealth Property Fund): Increase in average NABERS Energy rating from 2.6 to 4.1 stars from 2005-2011. Portfolio average target of 4.5 stars by 2012. (Exergy, 2012)
- General Property Trust: Portfolio average NABERS Energy rating in 2011 4.6 stars, compared to average rating in 2006 of 2.7 stars (GPT, 2012)

Other portfolios are known to have policies in place and have achieved upgrades, but adequate public data is not available.

Further evidence of the impact of the rating is that in 2000, there was essentially no floor space rated at 4.5 stars or above, and the benchmarks were specifically constructed to make 5 stars aspirational. At the time of writing, of the 856 current NABERS Office Energy Base Building Ratings, approximately 10% were 5 stars and 2.5% were 5.5 stars, excluding those buildings for which the purchase of externally supplied zero-emissions energy had contributed to the achievement of these ratings.

It is also noted that most of the office-exposed retail portfolios are now rating their retail properties and are engaging in improvement works.

5. Lessons Learnt

Twelve years of NABERS operation in Australia has led to a number of valuable insights into market transformation.

Positive lessons include:

- Performance based benchmarks are feasible and valuable in the market place where they enable benchmarking of energy/water use within the control of the stakeholder.
- Achievement of reductions in excess of 40% from average performance to market leading is quite feasible even for buildings with conventional technology. There are

many standard design older buildings achieving 4.5 and 5 star base building NABERS Energy for Offices ratings.

- Achievement of 5.5 stars is possible with modulations of standard technology such as chilled beams, low temperature VAV and cogeneration/trigeneration.
- Government is an important stakeholder as a market participant and can significantly influence market behavior through its procurement policies.
- Base building office ratings are particularly valuable in the market transformation process due to their ability to be used in procurement. Where such procurement mechanisms have less impact – such as lower grade offices with smaller, less powerful tenants, the impact of the rating is significantly lower.
- Key to the success of the NABERS rating system has been an underlying set of benchmarks which are essentially fair, reasonably accurate and stable. Absolute accuracy is neither possible nor necessary for a successful rating system.
- Retail shopping centre ratings are more complex but feasible. The exposure of the retail portfolio owners to an active and transforming office market has assisted adoption of NABERS in the retail sector. Corporate social responsibility policy appears to be driving this activity rather than the more direct market actions visible n the office sector.
- Hotel ratings are of interest to the industry but in the absence of market drivers for this, adoption has been slow, but positive.
- Voluntary operation can, and has been, highly successful in the presence of adequate market drivers for adoption. Mandatory operation has become possible because of the credibility of the scheme in voluntary operation,; the value of mandatory operation comes in application to market sectors that do not have an adequate voluntary uptake; for base building ratings this has been the mid-grade market which is not greatly exposed to tenants with sufficient market power to demand high NABERS ratings as a procurement requirement for new leases.

Challenges include:

- Where there is no market driver, it is difficult to engage the same level of interest and market transformation as achieved with the base building ratings. Thus for instance, tenancy ratings – which have fewer market drivers - have not achieved the same level of success in market transformation as the base building ratings. Indeed, it is notable that the gap in efficiency culture and practice between building owners and tenants in the high end of the market is increasingly stark, even in buildings where tenants have sought high base building ratings.
- While the base building/tenancy split is fundamental to the success of the rating system, it is also a major challenge in that it forces the prescription of firm boundaries in a situation where boundaries are not necessarily conducive to optimum efficiency outcomes. NABERS manages this issue well through the use of boundaries that are appropriate and efficiency-optimising for the vast majority of the market, but inevitably there are some situations where the definition of strict boundaries does not lead to optimum whole-building outcomes. Furthermore, the prescription of boundaries inevitably leads to attempts to "game" these boundaries which impose an ongoing quality assurance burden on the scheme; indeed much of the content of the rules that govern the performance of ratings is associated with the correct identification and treatment of these boundaries.
- There are differences between the operation of buildings in temperature climates and tropical climates due to the far greater potential for control issues in the former. In

Australia, the tropical sector of the market is much smaller than the temperate sector and as a result has created a number of challenges for benchmarking over the life of the scheme.

- Management of a nationally consistent rating in the rather fragmented state structure of Australia has not always been conducive to the best long term outcomes due to the sheer number, diversity, resource levels and differences in interests and aspirations across the multiple administrations. This has had particular ramifications for the office rating, which has significant state-to-state benchmarking difference due to the progressive nature of the roll-out of the scheme. However, other benchmarks have been able to establish a more nationally uniform approach due to the credibility established by the energy rating.
- Regulation for mandatory ratings is a mixed blessing. Since the Building Energy Efficiency Disclosure Act has come into force, the politics surrounding the operation of the scheme have increased massively and it has become far harder to change the system, even where such change is known to be necessary.

Overall, the lesson learnt is that a well structured and targeted market-based mechanism can deliver significant efficiency gains by turning efficiency from a technical issue into core business.

5.1. Forward Actions

The rating scheme has achieved a high level of maturity and success but as always there are opportunities for improvement. In particular:

- After 12 years, it is time to review and update the NABERS office Energy benchmarks and rating systems using recent data, and potentially shift the rating from a normalized emissions system to a variable benchmark system. This also needs to include nationalization of the benchmark, which is currently discontinuous from state to state.
- There are actions in hand to introduce a “multi-tool” which will enable buildings of a mix of types for which ratings currently exist to be rated as a single, mixed use object.
- NABERS for Data Centres is due to be released in late 2012
- NABERS is currently being adapted for extension to New Zealand.

It is noted that the NABERS model has strong potential for extension into other countries, especially where there is appropriate separation of base building and tenancy consumption.

6. Conclusions

Across 12 years of operation, NABERS has become a major influencing factor on the energy efficiency of the Australian office market, and has directly driven a number of major portfolios to reduce emissions by in excess of 40%.

The success of the scheme has been driven by the use of different ratings for base buildings and tenants, enabling tenants, in particular, to use the base building rating as a procurement criterion for new buildings and leases. This has created a significant market driver that has linked efficiency to lettability and thus decoupled efficiency expenditure from energy pay-back. Major portfolios have achieved savings in excess of 40% across base building performance, reflecting the strength of this driver. Governments at state and federal levels have played a crucial role in this by setting minimum NABERS requirements for base building performance for new government buildings and leases.

An important lesson from the development of the scheme is that the rating tool is only one small but important part of the overall machinery of the scheme. By creating a rating, one is setting a standard in which a very wide range of stakeholders have interest, and a great deal of conscious effort is required to manage the interests and expectations of these stakeholders while maintaining the technical integrity of the scheme. The long period of voluntary operation of the scheme was definitely helpful in this respect, as mandatory operation tends to discourage change, even where such change is desirable.

6.1. Acknowledgements

NABERS is owned and developed by the NSW government. The NSW Government administers NABERS on behalf of the Australian, State and Territory government nationally. For more information on NABERS see www.nabers.gov.au. The author has participated in the program as a developer of the rating system and as an auditor of NABERS assessments on behalf of the NABERS administrator.

The author wishes to thank all of the many people involved in the development and operation of NABERS over the past 12 years, and in particular: Nigel Isaacs, Sue Salmon, Chris Bloomfield, Matthew Clark and Yma ten Hoedt.

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Enhancing Building Performance Through More Responsive Maintenance System

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Abstract:
Previous studies have applied different techniques and concepts to planning, designing and executing construction projects. However, few studies have been conducted in maintaining such projects. Maintaining and operating any constructed facility costs more than its initial cost. The aim of this study is to improve maintenance processes by simulating the concept of multi-skilled technician to an existing maintenance process. Statistical data and maintenance process map of Saudi Consolidated Electric Company (SCECO) are modeled in Extend+BPR® to be an experimental tool for evaluating the benefits of multi-skilled technicians. The simulation models of this study showed significant improvement in both preventive and corrective maintenance processes.

Keywords:
preventive, corrective, maintenance, simulation, MST

1. Introduction

One way to save cost and add value to an organization is to improve its maintenance system. In the Kingdom of Saudi Arabia, a high percentage of the government's expenditure has been directed toward maintenance and operation projects (Al-Arjani 2002). Therefore, any reduction in resources applied to building maintenance will be reflected on the national economy (Horner *et al.* 1997). There are many actions in reducing maintenance cost (e.g., process redesign/reengineering, better utilization of resources, reducing errors and reworks, … etc). This study aims at reducing cost of maintenance work orders by employing multi skilled technicians. The concept of multi skilled technician (MST) refers to a labor utilization strategy in which workers learn more multiple skills in one or more trades outside their primary trade (Carley *et al.* 20003).

Manpower plays a significant role on the quality of maintenance. This is because the costs of maintenance labor constitute the largest block in the maintenance costs (Mjema 2002). Therefore, enhancing labor performance will add value to the whole maintenance process. One way to enhance labor performance is to employ the concept of MST. This has proven its success in the manufacturing industry where it could be applicable to the building industry.

The concept of MST implies that a technician can perform more than one work order (WO) of different services (e.g., mechanical, electrical, and so forth). For example, installing a water heater needs a plumber and electrician to complete the job in a traditional maintenance system. With MST principle, this work order can be done by one technician instead of two. In this way work orders will wait less time in the maintenance system, thus increasing the throughput and enhancing the availability of a facility. Thus, the objective of this study is to assess the potentiality of employing multi-skilled technicians to an existing maintenance process using computer simulation.

Employing the concept of MST has numerous advantages which include: overcoming labor shortage (Lobo and Wilkinson 2008), responding to unexpected events without consulting a supervisor (Carley *et al.* 2003), improving quality (Carley *et al.* 2003), enhancing process flexibility (Organ *et al*. 1998), reducing cost (Carley *et al.* 2003 and Pintelon *et al*. 2006), and increasing productivity (Oral *et al.* 2003 and Pintelon *et al*. 2006).

Several researchers modeled maintenance processes to evaluate certain issues. The simulation models of Ip *et al.* (2000) and Mjema (2002) focused mainly on capacity planning in order to determine the appropriate number of the maintenance personnel. Duffuaa *et al.* (2001) developed a generic conceptual simulation model that consisted of seven modules, such as materials and spares supply. The modules of Duffuaa's model are designed to fit common maintenance system requirements but not for specific issues like MST. Wang and Hwang (2004) integrated qualitative method in their mathematical model to include human factors (e.g., human errors) to find the optimum balance between the costs and benefits of maintenance. This study incorporates another qualitative factor, which is MST, in quantitative simulation models. The concept of MST and its impact on building maintenance was not thoroughly discussed in previous studies.

It is true that a multi-skilled technician costs more than a single skilled technician. This study argues that the total cost of completing a job may decrease as the maintenance system with MST will be more responsive and faster, which will save time and effort. To test this hypothesis, a maintenance system for Saudi Consolidated Electric Company (SCECO), a leading company in Saudi Arabia, was selected as a case study. The main focus is the head quarter maintenance division located at SCECO-East. This division is responsible for maintaining all administrative buildings, which consist of 30 buildings of various sizes and functions.

2. Methodology

Field surveys and interviews aimed at collecting data necessary for building two types of models: static and dynamic models. Static model, on one hand, is a two dimensional representation of the process by mapping it using flow chart techniques. A flow chart will show the logic, the activities and the decisions involved in performing maintenance work orders. On the other hand, dynamic model is referred to computer simulation where one can experiment the potentiality and limitation of certain concepts.

Out of the 60 employees working at the maintenance division, 23 were interviewed. The interviews were conducted in different phases to make sure that the collected information is accurate and to refine the maintenance process maps and the simulation model.

2.1 The Development of the SCECO Maintenance Process Map

The maintenance process is divided into two main sub-processes: 1) Preventive Maintenance (PM), and 2) Corrective Maintenance (CM) as shown in figure (1). The two sub-processes are interrelated where under certain conditions some preventive maintenance work orders are converted into corrective maintenance work orders.

Such maps played a role in visualizing the work process flow and made discussions with interviewees easy and fruitful. The author facilitated further discussions by asking the following questions, which were taken from Back and Bell (1994) and Al-Sudairi (2007):

- Which activity must be finished before the next activity can begin?
- Can this activity occur concurrently with any other activities?
- Which resources are required to perform these activities?
- What are the deliverables of these processes?
- How are the deliverables transmitted internally and externally?
- How often must certain activities be repeated?
- How long does it take to finish an activity? This is accomplished by having each interviewee give three time estimates for each task that he is responsible for (minimum, most likely, and maximum).
- What are the probabilities of decision outcomes?

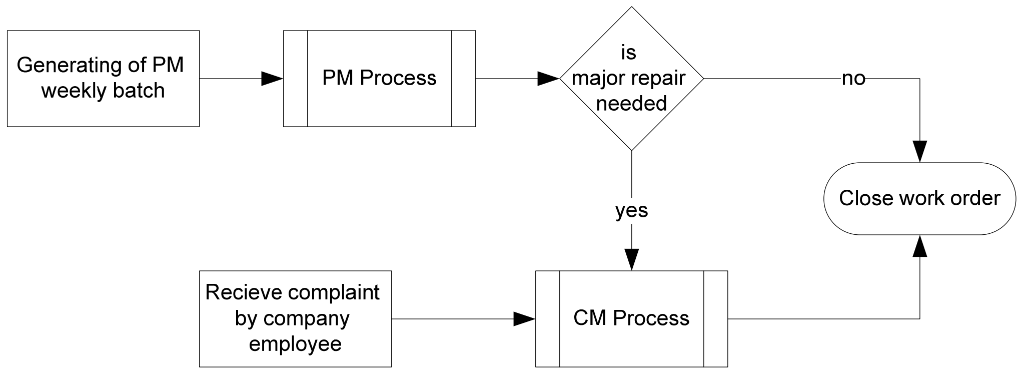


Fig. 1: Basic relationship between PM and CM processes.

Figure (1) shows the interrelationship between PM and CM processes at a macro level. However, figure (2) stipulates full details of activities and decisions of PM process. For detailed CM process, readers are advised to see the study of Alsudairi (2005).

PM work orders are generated in batches once a week. The PM engineer prepares the weekly batch, allocates work orders according to each maintenance unit, and submits work orders to each unit whereby they go through the normal PM process. There are five maintenance units under the Head Quarter of Maintenance Division. Each unit is responsible for operating a certain type of service. Under each unit there are several workshops that vary in size from one unit to another. In this study only units that are related to building maintenance are included. The selected units are: (1) Electrical Repair Unit (ERU), (2) Air Condition Repair Unit (ACRU), and (3) Facility Maintenance Unit (FMU).

The PM work orders are either closed after completion or transferred to the CM process. On the other hand, CM work orders enter the maintenance system by a request of a technician or a complaint from a customer. During the routine check, a technician who is performing PM work order can't continue the job because it requires major repairs. Thus, this PM work order will be converted into a CM work order or, in many cases, a CM dispatcher receives a complaint from a customer. This complaint will enter the maintenance system as a CM work order.

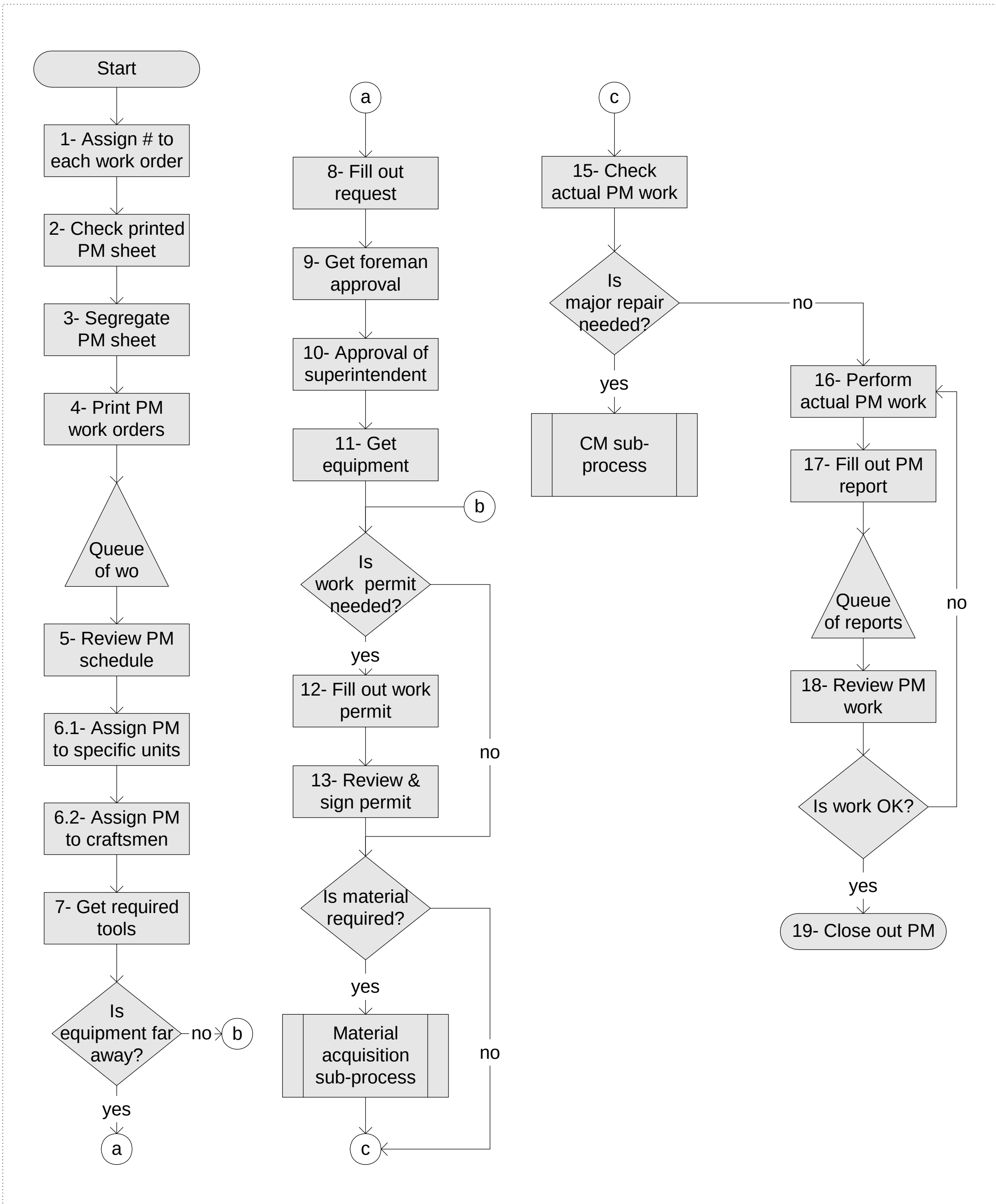


Fig. 2: Preventive maintenance detailed process map.

2.2 Collection of Quantitative Data

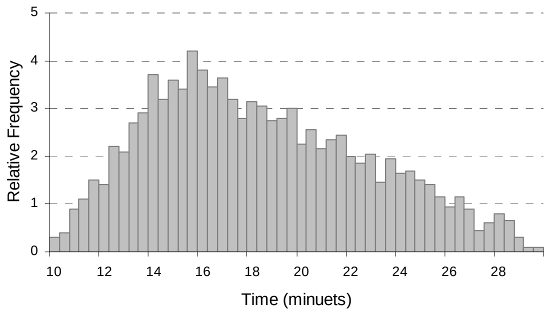
Measuring activities' durations is one of the critical inputs to the validity of simulation models. It is apparent from the process map presented in figure (2) that maintenance processes contain many activities. The activities' duration were estimated by experts who were asked to give three times (most likely, maximum, and minimum) for each activity in the PM process as shown in Tables (1). Quantitative data for CM activities can be found in the study of Alsudairi (2005). The sixth column in table (1) presents the average time for each activity that was calculated according to *Beta* distribution assumptions. The reason behind using *Beta* distribution is because of its adequacy and flexibility for most construction activities (AbouRizk *et al*. 1994 and Alkoc and Erbatur 1997). The average time was useful in constructing the initial simulation model for verification purposes. The three time estimates were entered for each activity in the simulation model. Figure 3 (a & b) shows an example of one PM activity and another CM activity in which Extend+BPR converts such estimates into distributions. The same procedure was done for all activities. According to Cassady *et al.* (2001) probability distributions of activities in simulation models ensure a more realistic portrayal of real systems.

Table 1: Time estimates in minutes of Preventive Maintenance activities.

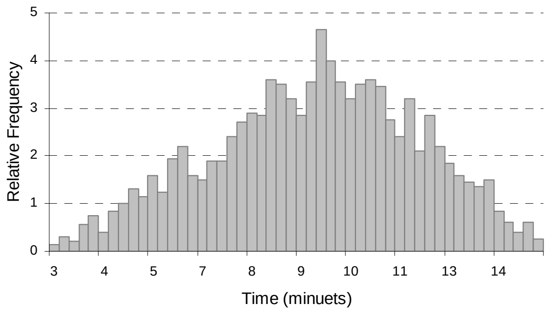
No.	**Task**	**Minimum**	**Most likely**	**Maximum**	**Average**
1	Assign no. to each work order	5	8	12	8.17
2	Check printed PM sheet	4	8	10	7.67
3	Segregate PM sheet	2.5	4	7	4.25
4	Print PM work orders	5	10	15	10.00
5	Review PM schedule	3	7	11	7.00
6	Assign PM to specific units/craftsman	2	4	7	4.17
7	Get required tools	10	15	30	16.67
8	Fill out a request	10	15	30	16.67
9	Get foreman approval	10	18	25	17.83
10	Get approval of superintendent	11	20	30	20.17
11	Get equipment	10	15	30	16.67
12	Fill out a permit	30	45	60	45.00
13	Evaluate and sign permit	8	10	15	10.50
14	Material acquisition	3	30	90	35.50
15	Check actual PM work	10	11	15	11.50
16	Perform actual PM work	60	120	240	130.00
17	Fill out PM report	4	7	10	7.00
18	Review PM work	4	6	7	5.83
19	Close PM work order	2	3	4	3.00

Another important piece of information is the probability of occurrence of the decisions associated with both maintenance processes as shown in figure (2). For instance, a work permit is required whenever a WO is associated with hazardous equipment/material or it is located in a restricted area. To quantify this information, previous records of WOs were reviewed to find out the probability of each decision outcome by calculating the percentage of WO that needed work permits. This method of quantifying decisions is the one most used by several researchers (Hansen 1997, and Laguna and Marklund 2005).

With respect to maintenance work orders, it is also important to know whether they are preventive or corrective and to what maintenance unit they belong to. Figure (4) summarizes the type and percentages of maintenance WO for 52 weeks which indicates that most work orders are handled by ACRU (45% of PM WO) while FMU got the least (14% of PM WO). These percentages are useful in simulating the flow and type of WO. In fact, modern simulation packages are object-oriented. The object in this case is the maintenance work order whether preventive or corrective. Logic and issues related to the simulation model will be discussed in the next section.



(a) PM Activity # 11- *Get Equipment* distribution



(b) CM Activity # 2- *Enter Complaint* distribution

Fig. 3: Two examples of activities' time distributions in both PM and CM processes.

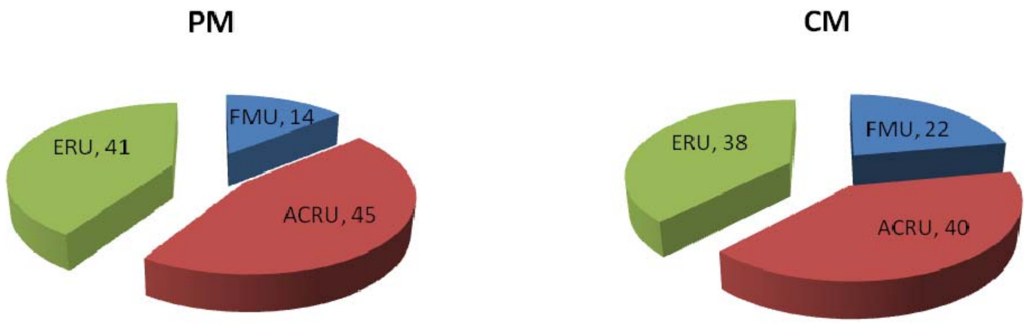


Fig. 4: Types and percentages of maintenance WOs.

Manpower cost is also another essential modeling input in order to compare the traditional system, which referred to as "as-is", with the proposed system, which referred to as "to-be". The cost of different technicians is gathered from SCECO personnel records. The cost of technicians varies according to their qualifications and years of experience. However, an average cost per hour was calculated so that it represents most technicians which is \$15.2 per hour; on the other hand, the cost for a multi-skilled technician is \$22.7 per hour (SCECO-Support-Facility 1999).

2.3 The Maintenance Simulation Model

To model maintenance processes, data collected in previous steps requires transfer into simulation notation. Each simulation package has its own form of activity notation or language (Back and Bell 1994). For this study, Extend+BPR was selected as the simulation modeling package because of its flexibility and adaptability in modeling lengthy complex processes (Krahl 2002).

Extend+BPR is an object-oriented simulation tool. In other literatures objects are referred to as "flow units" (Halpin and Riggs 1992). The word "flow" implies that objects are dynamic and as they move in a process they may change their attributes or may gain more. Knowing what and how of an object is very crucial in building a credible accurate simulation model.

Objects vary according to the system they belong to. Thus, the simulation models created for this study are designed to examine the flow of maintenance work orders for both PM and CM. This feature of object-oriented simulation packages allow the determination of how long each WO stays in a process that includes both processing time and waiting time. In doing so, one can accurately determine process efficiency.

Figure (5) shows a small portion of the maintenance model that was built on Extend+BPR. The most important part of any Extend+BPR model are the blocks, the libraries where blocks are stored, the dialogs associated with each block, the connectors on each block, and the connections between blocks (Krahl 2002). A block specifies an action or process; it is used to represent an activity, an event or a function of a model. Some blocks may simply represent sources of information. Others may modify information as it passes through them. Information comes into the block and is processed by the program that is embodied in the block. The block then transmits information out of the block to the next block in the simulation.

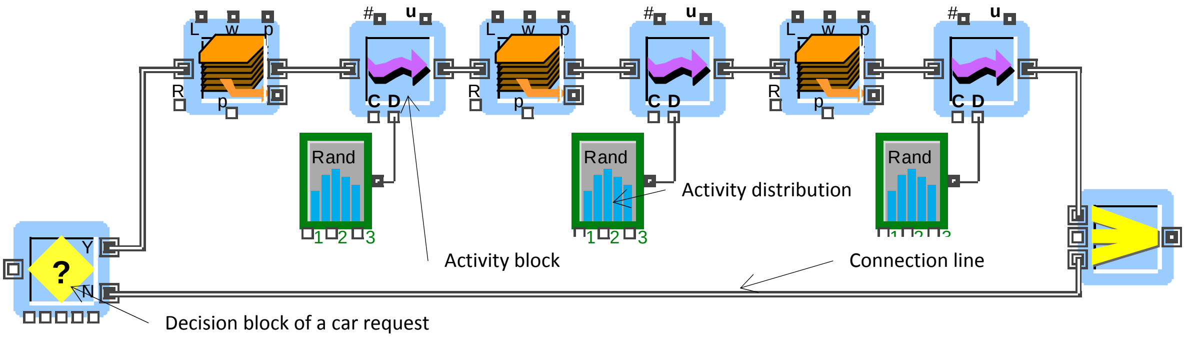


Fig. 5: Portion of the maintenance simulation model that mimics the car request activities.

A successful modeling is totally dependent on the development of a base-line model that accurately mimics the present work flow process and the interrelationships among various tasks (Ardhaldjian and Fahner 1994). Before experimenting with simulation to evaluate the effect of MST, it is necessary to validate the traditional model. A comparison between the model outcomes and the data gathered from both processes on site was made as shown in table (2) to ensure the validity of the model.

Table (2) shows two sets of data, actual and empirical, for the total cycle time to close out one work order of either PM or CM and the number of completed work orders per week. The actual data was gathered from previous records for both processes whereas empirical data was gathered from simulation models. Notice how close the two sets of data which proves that the simulation models are valid and ready for evaluation.

The validated "as-is" model was used as a reference point to measure and compare the impact of MST on maintenance processes. The concept of MST implied some changes to both PM and CM processes. By looking into the process map presented in figure (2), activities with numbers 3 (*Segregate PM sheets*), 6.1 (*Assign PM to specific unit*), and 6.2 (*Assign PM to* *craftsmen*) are not always required because the superintendent can most of the time assign work orders directly. Running the simulation model with these changes and being capable of meeting most maintenance orders due to MST, led to a leaner system that is going to be discussed further in the coming section.

Table 2: Comparing the outcomes of the as-is model with the actual data.

	Cycle Time (hours)		Throughput (WO/week)	
	Actual	**Empirical**	**Actual**	**Empirical**
PM	16	15	110	115
CM	22	20	80	76

3. Results Analysis

Table (3) compares results of both the “as-is” and the “to-be” maintenance models in terms of cycle time, labor cost, crew utilization and throughput. One may notice the remarkable improvement gained by implementing the concept of MST. Regarding the PM process, there is a 68% reduction in cycle time and 56% reduction in cost. In terms of crew utilization and throughput the PM process improved by 45% and 27%, respectively. Results with respect to the CM process are encouraging as well, but, they are less than those in the PM process. The difference in improvement is due to the fact that the maintenance policy in SCECO gave more priority to PM work orders. These improvements are attributed to the high response to work orders where they wait for a short time in the maintenance process. The role of the maintenance superintendent and the activities associated with him are markedly reduced in the “to-be” model.

Table 3: Comparing results of both the “as-is” and the “to-be” maintenance models.

	Cycle Time (hours)		Labor Cost ($/WO)		Utilization		Throughput (WO/week)	
	as-is	to-be	as-is	to-be	as-is	to-be	as-is	to-be
PM	15	4.8	295	129	42	87	110	140
CM	22	9.5	420	201	42	87	80	98

Figure (6) compares the crew utilization of the two simulation models where one can see the remarkable difference between the two. The ERU, ACRU and FMU curves belong to the utilization rate of the “as-is” model whereas the MST curve belongs the utilization rate of the “to-be” model. Almost 87% of the technician time in the “to-be” model is spent on performing maintenance work orders. One may notice how steady the “to-be” utilization curve is along the simulation run time; it has also gained a high rate of utilization right from the beginning as opposed to the “as-is” utilization curves. The utilization rate is the same in both processes, whether PM or CM, as all technicians are responsible for both types of work orders. The enhanced utilization of technicians contributed to the increase in throughput where 140 PM WO/week and 98 CM WO/week are accomplished. This is comparable to the results of Mjema study (2002) who found a 91% improvement of utilization rate.

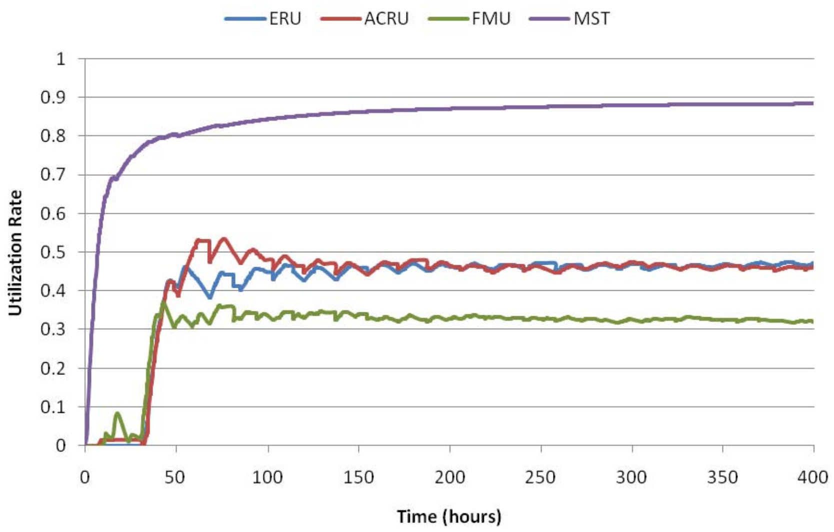


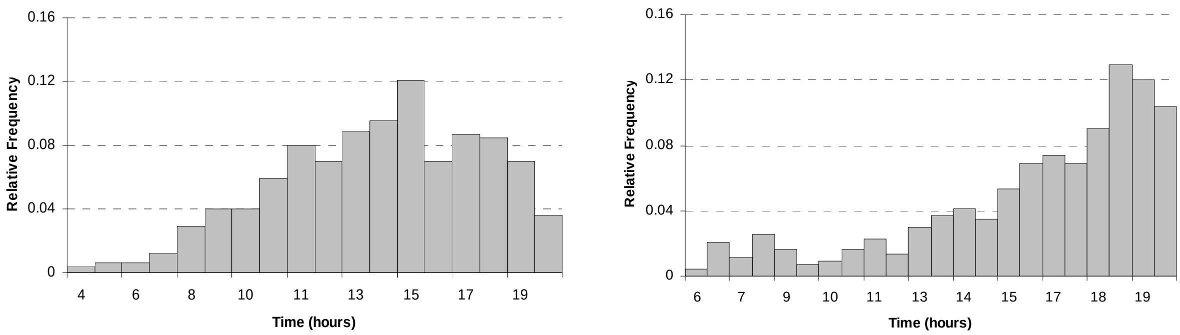
Figure 6: Comparison of technician utilization of the two simulation models.

On the contrary, crew utilization in the “as-is” maintenance process is very low. It is as low as 34% in facility maintenance unit (FMU) as shown in figure 6. This is because the work orders have to go through long paper work before they get assigned to a specific maintenance unit. Once these work orders reach their units, the superintendent checks the availability of his craftsmen who may be busy in other work orders. Another reason that led to low utilization is the type of work orders that may vary according to seasons. For instance, in summer there is more demand on A/C repairs and checkups than in winter. This necessitates a responsive and adaptable system that can meet most maintenance work orders. One way is to provide more skilled technicians who can handle most maintenance services.

Figures (7) and (8) present cycle time distribution of work orders for both PM and CM processes in the “as-is” and the “to-be” models. Again this shows the magnitude of the potentiality of MST. The work orders in the “as-is” system take longer to be completed where it takes an average of 15 hours compared to 4 hours in the “to-be” system. Besides, the long time of WO in the “as-is” system one may notice the huge variability in both distributions as shown in Figure (7). There is a 16-hour difference in the “as-is” preventive maintenance process, which is almost the same in the corrective maintenance process. The huge variability indicates a weakness in the existing process. In fact, Narayan (1998) concluded that process variability is a major source of cost increase, which is the case in the “as-is” process.

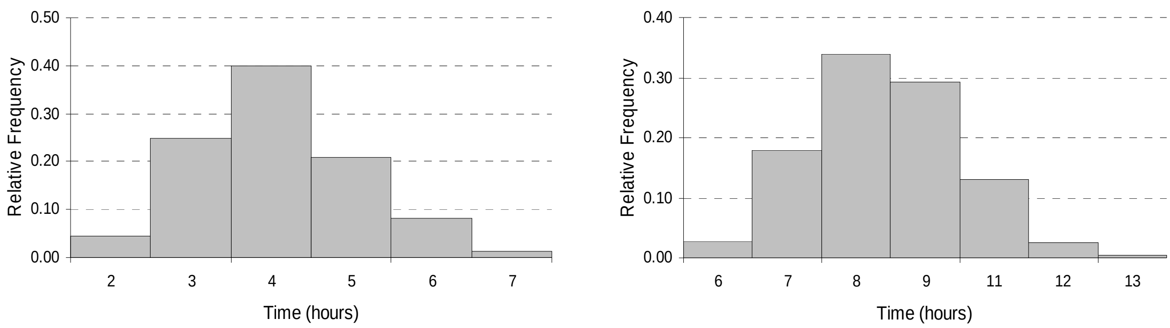
The number of multi-skilled technicians modeled in this study was almost one third the number of “as-is” technicians. This affirms another advantage of MST concept to the construction industry that is facing more demands and challenges to be faster and more productive, and to meet the shortage in skilled laborers. To overcome these demands and challenges, there is a need to invest more in training laborers in order to improve their skills in different services. This would enhance one major input, which is human resources, to construction/maintenance processes by adding more value to their outcomes and eventually to the final product or service.

The improvement gained by employing the concept of MST was relative to the “as-is” maintenance process practiced by SCECO, which contained huge amount of non-value adding activities. Looking back, figure 8 (a and b) shows that the “to-be” maintenance model has a better performance, but, work orders still go through variable time. It is not as variable as the ones in the “as-is” maintenance model. However, inefficiency still exists in the “to-be” model. This is because the emphasis of the current study is on multi-skilled technicians where the process stayed almost the same as in the “as-is” process.



(a) “as-is” PM cycle time distribution (b) “as-is” CM cycle time distribution

Fig. 7: Cycle time distribution for 2000 runs of the “as-is” maintenance process.



(a) “to-be” PM cycle time distribution (b) “to-be” CM cycle time distribution

Fig. 8: Cycle time distribution for 2000 runs of the “to-be” maintenance process.

Focusing on technologies also has a significant impact on leading to leaner processes. Many of the activities in the maintenance process of the case study can be done electronically. In doing so, some of the activities will be eliminated or the time needed to complete them is reduced which will expedite information transfer and enhance communication. For example, activities 8, 9 and 10 in the PM process can be mainly done electronically with minimal paper work, that is; work permits can be sent electronically to the superintend without the presence of a technician. While the technician awaits his superintendent’s approval, he can perform other work orders that will add value to the maintenance system. Indeed, integrating people, processes, and technologies is essential in adopting a system view of process management.

The presented case study is huge where there are many buildings of various functions and uses. The amount of maintenance work orders is expected to be huge and diverse as well. In situations like this, the MST concept may work well. In other situations where work orders are not as frequent/diverse as in this case study, an MST concept may not be very effective. The cost-benefit ratio of a multi-skilled technician may not be significant. This requires further investigation on the factors that influence the potentiality of MST.

4. Conclusion

This study evaluated the benefits of MST to a maintenance process of a leading company (SCECO) using object-oriented simulation package (Extend+BPR). Simulating the concept of MST led to significant improvement in terms of cycle time, labor cost, utilization and throughput. The average time and cost to complete one PM work order were reduced by 68% and 56%, respectively. Also, technician utilization and productivity improved by 45% and 27%, respectively. The performance of the PM process was better than that of the CM process because the former process was given more priority. Thus, the balance between the two processes requires more attention that may be achieved in future studies.

This study focused on people as one important aspect of process management. Extending maintenance technicians' breadth and depth of their skills will have a positive impact on their performance as well and eventually will add value to the final product or service. However, it is extremely important to look into maintenance processes as a system of different inputs that include people, materials and technologies in order to enhance their efficacy and value.

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Achieving Energy Performance in spite of complex systems and dis-jointed design

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Abstract:
The extensively refurbished heritage government department office building in Canberra's Parliamentary circle, has managed to achieve its target energy performance levels contrary to expectations following difficult design and construction processes, through careful and thorough commissioning and tuning.

The existing two storey 5,000m^2 sandstone building was completely gutted and brought to a new life as a head office for one of Australia's federal government departments. The building was stripped back to a bare shell, before being re-created to a Grade A office with numerous tenant systems, including a 125kW data centre with a series of complex multi-layered alarm and protection systems.

Given the extent of incomplete or contradictory designs, the commissioning team needed to carry out substantial planning, coordination and framing of test scenarios in order to bring all issues to a close, all the while being cognisant of the final desired energy performance outcome and close scrutiny by the Tenant representative of all commissioning planning and witness testing.

This paper presents an overview of the challenges that needed to resolved during the course of the commissioning and tuning processes to achieve/maintain the target energy performance outcome (4.5 Stars NABERS – approximately 70-75kg/CO_{2e}/m^2/year) after 12 months of occupation and operation. In order to aid understanding, we have assessed the procedures and steps taken against the Soft landings guidelines and core principles.

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Keywords:
Commissioning, energy performance, heritage, refurbishment, tuning.

1. Introduction

This case study looks at the successful achievement of the desired energy performance targets in an office refurbishment project and asks "Why", what did we do right?

The objective of this paper is to demonstrate that with focussed effort and attention during the commissioning and tuning phase of a project, that the target performance can be achieved within a reduced timeframe.

In addition, it has been shown that with the application of the Soft Landings core principles and some additional elements, that industry best practice outcomes can be achieved in a timely manner without compromising operational function and thermal comfort.

This project has confirmed that the Soft Landings core principles carry substantial benefit when applied diligently.

This paper presents an overview of the challenges that needed to be resolved during the course of the commissioning, tuning and handover processes to achieve/maintain the target energy performance outcome.

Fig. 1. Aerial view of 2 National Cct office building – Canberra Australia

Fig. 2. Sandstone façade, heritage listed office building – Canberra Australia

2. Background

The existing two storey 5,000m2 sandstone building was brought to a new life as a head office for one of Australia's federal government departments. The building was re-created as a Grade A office with numerous tenant systems, including a 125kW data centre with a series of complex multi-layered alarm and protection systems.

The refurbishment was planned and designed as an integrated fit-out project to meet the specific needs of the end occupant, a high security federal government department. These needs were recorded in a Functional Requirements Brief (FRB) by the occupant/tenant representative and provided to the design team and owner at commencement of the project.

The head contractor was engaged under a standard "Lump sum" contract. While the desired performance targets were indicated in the Specifications, there was no specific legal requirement to deliver the target performance outcomes.

During the course of the construction works on site, a number of core design issues were identified and the owner took steps to have these rectified. This occurred either through the use of an independent electrical design consultant or through engaging the mechanical contractor in a Design and Construct contract.

As a risk management initiative, shortly before commissioning commenced, the Contractor engaged an independent energy efficiency design and commissioning management consultant.

Given the extent of incomplete/contradictory design elements, the commissioning team needed to carry out substantial planning, coordination and framing of test scenarios in order to bring all issues to a close, all the while being cognisant of the final desired energy performance outcome and close scrutiny by the Tenant representative of all commissioning planning and witness testing. The team also prepared comprehensive training and tuning plans, which have proved to be of significant value.

In spite of the difficulties, the extensively refurbished heritage building managed to achieve its target energy performance levels contrary to expectations, through the application of the CIBSE Soft landings principles and a few additional planning and analysis steps.

3. Achieved performance

After 1 year of operation and occupation, the base building energy (emissions) performance is tracking at a little better than the target level – 4.5 Stars NABERS (National Australian Built Environment Rating), while the tenancy (non-data centre) energy performance is well above target. For buildings located in NSW and ACT, 4.5 Stars equates to approximately 87 $kg/CO_2/m^2/pa$ [CO2-e/m²] (NABERS, 2012)

The graphs in Figures 3 and 4 below commence at the time of occupation, October 2011 and shows there were a few digressions from target before the occupants and systems "settled in".

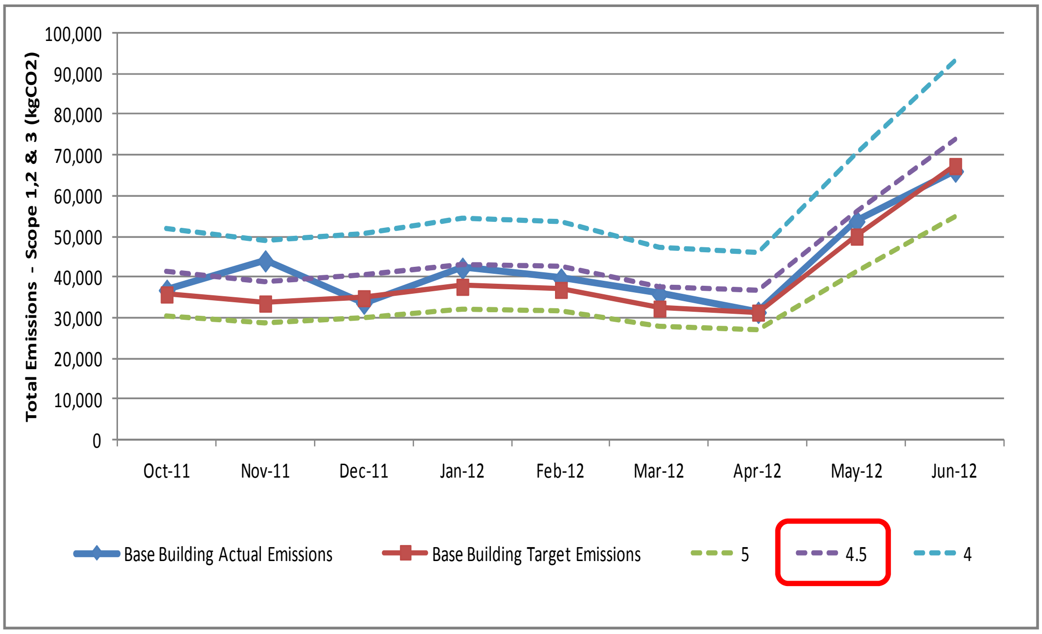

Fig. 3. Base Building Total Emissions compared with NABERS star bands

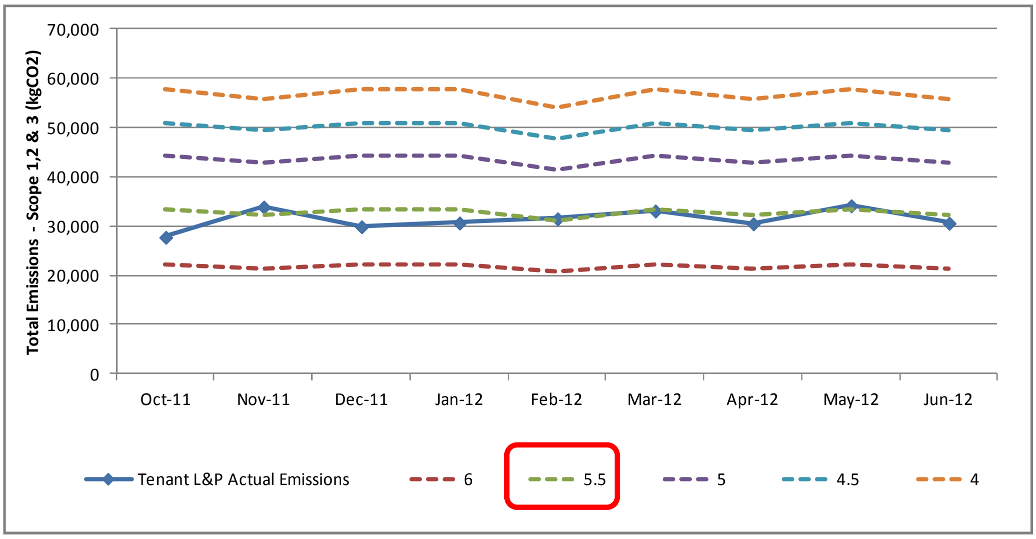

Fig. 4. Tenancy light & power emissions compared with NABERS star bands

Experience on a number of other energy efficiency projects has shown that it is uncommon for significantly refurbished or new buildings to achieve their desired energy targets in such a short time period. In the majority of cases reviewed, most buildings only achieve target 18 months post occupation. The performance generally fluctuates dramatically over the first 3-6 months as systems are tuned to respond to the actual building loads.

4. Soft Landings framework

The Soft Landings framework is an open source construction protocol/procedure developed by BSRIA and Usable Buildings Trust for the improved delivery, hand over and operation of high performance buildings.

The framework has been developed to work alongside the complete design, construction and hand-over processes and beyond. It aims to close the loop between each of the stages and feedback into new designs. There are 5 stages defined under the frame work, starting with “Inception and briefing” all the way through to “Extended after-care years 1-3”

Soft Landings has 12 core principles that guide the application of the process. (BSRIA, 2012)

In order to carry out a structured assessment of the process used in achieving the target energy performance on this project, we have used the Soft Landings framework and core principles to assess the approach and methodology. This is not to prove/disprove the Soft landings concept, but rather to reinforce how the implementation of a structured continuous performance focused process is able to deliver the required outcomes.

Due to our late engagement on this project, the assessment and review has been focussed on the latter 3 stages:

- Pre-handover,
- Initial Aftercare and
- Years 1-3 Extended Aftercare

5. Project design and commissioning issues

As noted above, during construction there had been substantial issues identified with the design of the engineering systems, many of which had not been resolved.

At the time of commissioning, these issues once again became apparent when sub-contractors were unable to determine clear testing acceptance criteria.

This was exacerbated by the lack of attendance by the design engineers at all the commissioning meetings, resulting in the sub-contractors having to establish “acceptable” commissioning standards based on experience and interpretation of the specifications.

A further complication was the extensive alarm and protection systems installed into the data centre. The tenant requirements brief called for all of these systems to report through more than one “head end”, while the engineering specifications lacked any detail of how this integration was to be achieved.

Another significant constraint was the security requirements of the project which prohibited the use of cameras, mobile phones or other electronic devices on site. This was especially troublesome during integration testing and also in the tuning stage where no remote access to control systems was allowed.

6. Methodology

The methodology used on this project is based on the Soft landings principles broken down as follows:

Planning stage

- Development of a commissioning plan

- Determination of clear commissioning objectives with sub-contractors
- Establish leadership, and define roles and responsibilities
- Development of commissioning procedures for non-standard situations

Implementation stage

- Structured and frequent communications (feedback loop)
- Continuous monitoring and verification of testing procedures
- Development of handover, training and tuning plans
- Registration of issues requiring further attention

Tuning stage

- Completion of As-builts, O&M Manuals and deliver training
- Engagement with Building manager and maintainers
- Provide leadership of tuning and monitoring activities
- “Close out” issues identified during implementation stage

6.1. Planning

Directly after engagement of the independent commissioning manager, work commenced with the Head Contractor to develop a clear commissioning plan. The plan included the following elements:

- Operational objectives and performance outcomes
- Roles and responsibilities
- Commissioning stages and cross-system integration testing
- Delivery schedule

As a result, the engineering sub-contractors were required to explain their intended commissioning approach and timeframes. It was clear that the sub-contractors required a defined structure and guidelines to follow.

Weekly commissioning planning meetings were restructured to move to a focused discussion on testing procedures and proving reliable yet efficient operation of systems. In addition, collaborative planning of the control system integration matrix was carried out. The change in focus of commissioning meetings required the whole team to take ownership of the systems they were installing and identify how they could be best commissioned. Minutes covered items such as:

- Review of previous weeks testing progress – recording failed or incomplete tests
- Identification of testing and witnessing in the following fortnight (look ahead schedule)
- On-site scope items and risks impacting commissioning
- Documentation reviews (Commissioning plans, test plans, As-built drawings and O&M manuals)
- Assessment of control and measurement system reporting

The meetings were attended by the owner’s representative, project manager and tenant representatives. All of whom actively participated and showed significant interest in the delivery of performance outcomes, and did not simply focus on practical completion.

As each member became aware of the challenges and the need to achieve the performance outcome, with clear leadership and drive, they were able to contribute to the development of the commissioning pathway. They moved from a hap hazard approach to commissioning, to one with a structure plan, with defined expected outcomes.

6.2. Commissioning implementation (Pre-handover)

With increased interest and commitment from the team, many of the outstanding design issues were resolved and agreement reached on testing methodologies. This included the development of an extensive controls integration matrix, covering all control, alarm and warning systems.

The improved progress monitoring and reporting, substantially increased the transparency of the process resulting in better "buy-in" by the owner and tenant representative, and commissioning planning meetings changed from confrontational encounters to problem solving sessions.

Commissioning of the control systems was carried out using a non-typical approach. Instead of the standard industry practice of single point-in-time verification of control operation, the adopted process included a period based analysis of operations. This included in-depth analysis of the operation of field controllers and equipment through their recorded activity in the control system trend logs. See example trend logs of the VAV's and AHU's operations in Figures 5 and 6) This process meant that all time scheduled and staging actions were fully validated and rectified ahead of handover.

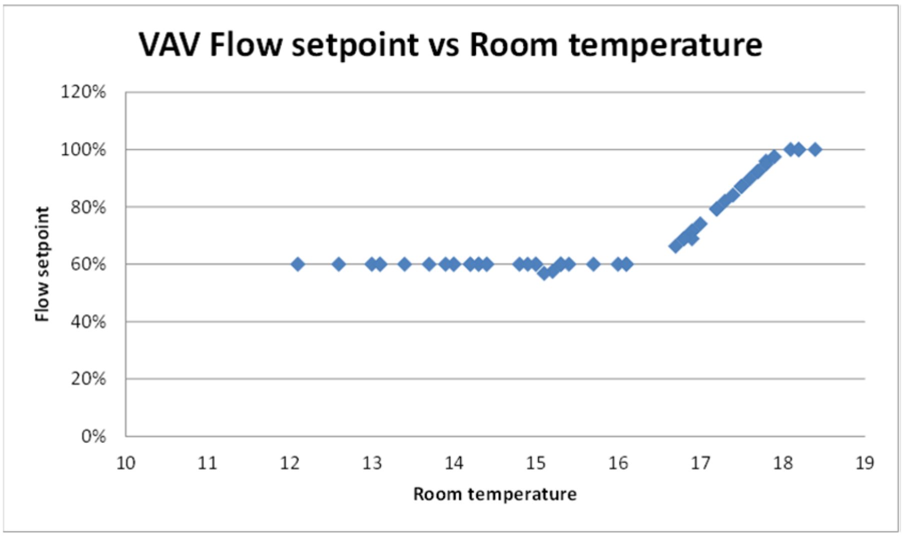

Fig. 5. Trend log confirming Flow set point algorithm (Moffitt, 2011)

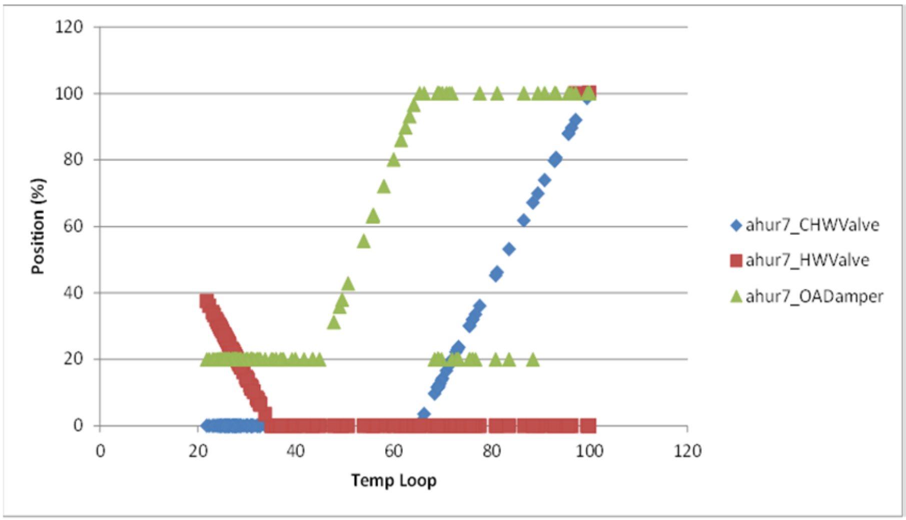

Fig. 6. Trend log confirming AHU response to temperature loop (Moffitt, 2011)

This verification of the control systems (specifically the BMS, lighting controls and generator load controller) identified a number of issues and defects that would need to be addressed once the building was occupied. In many cases this was because systems were under-loaded during commissioning as there were no occupants or tenant systems in place. These issues and defects were recorded and agreed with the owner for later resolution.

Another critical development was the preparation of the training and tuning plans. With the increased focus on performance outcomes, these plans provided team members with clear cut action lists that described the expected carry over from construction into the operational phase of the project.

6.3. Tuning stage (After care – year 1)

Following Practical Completion, a thorough review and verification of the As-built drawings and O&M manuals, played an important role in ensuring that the transition to operation by the tenants was as streamlined as possible.

Active involvement of the Building Manager and maintenance personnel commenced during the witness testing stage. However, this was ramped up at the time of Practical Completion to ensure that the maintenance team was comfortable with how the systems operated and understood the control systems and interfaces for day to day operations.

Directly after Practical Completion was awarded in September 2011 and occupation was complete, the team commenced with tuning the building and the engineering systems. There were a few issues with false alarms on the generator fuel indicator system and the daylight harvesting controls that required particular attention, although neither had any impact on energy performance.

Due to the high security requirements preventing remote log in to the control systems, the team members were forced to interact with the tenant representatives and in doing so, were exposed to direct feedback about performance and thermal comfort. This ensured that issues of thermal comfort and excess energy consumption were attended to immediately.

Comprehensive energy monitoring and analysis commenced directly after occupation and has continued each month, with detailed reports and recommendations prepared. These recommendations, together with the findings from the quarterly operations reviews were discussed with the tenant, maintenance service contractors and commissioning manager before being implemented. In this way, each recommendation is evaluated and agreement reached prior to making system changes.

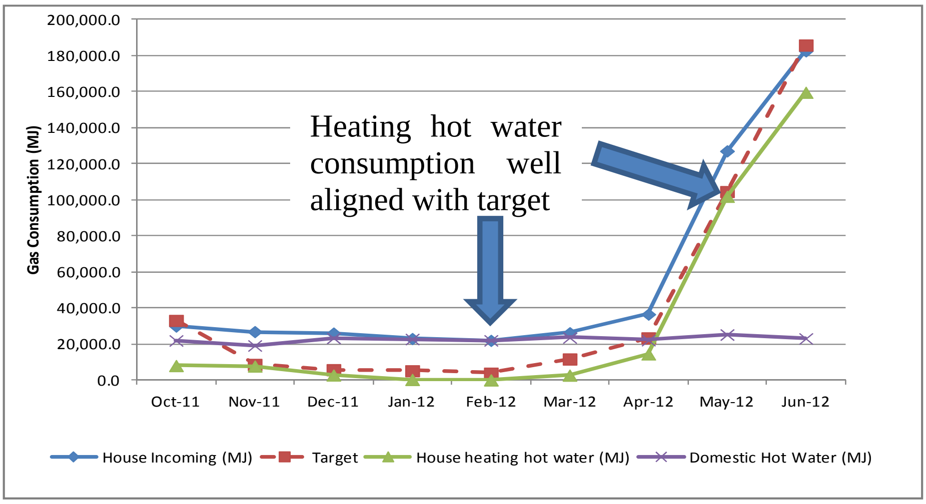

Fig. 7. Trend log of Base Building gas consumption – against target (Moffitt, Ardren, 2012)

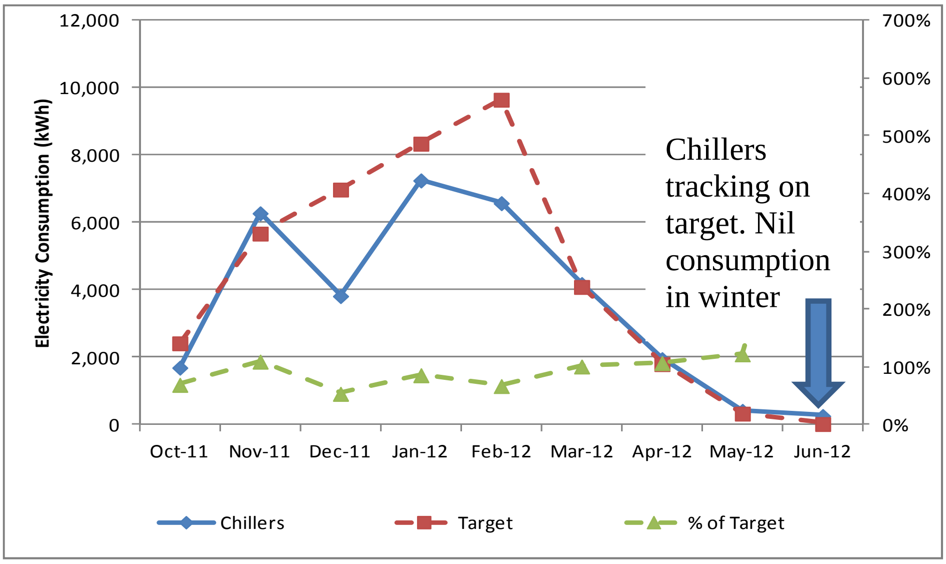

Fig. 8. Trend log of Base Building Chiller energy consumption (Moffitt, Ardren, 2012)

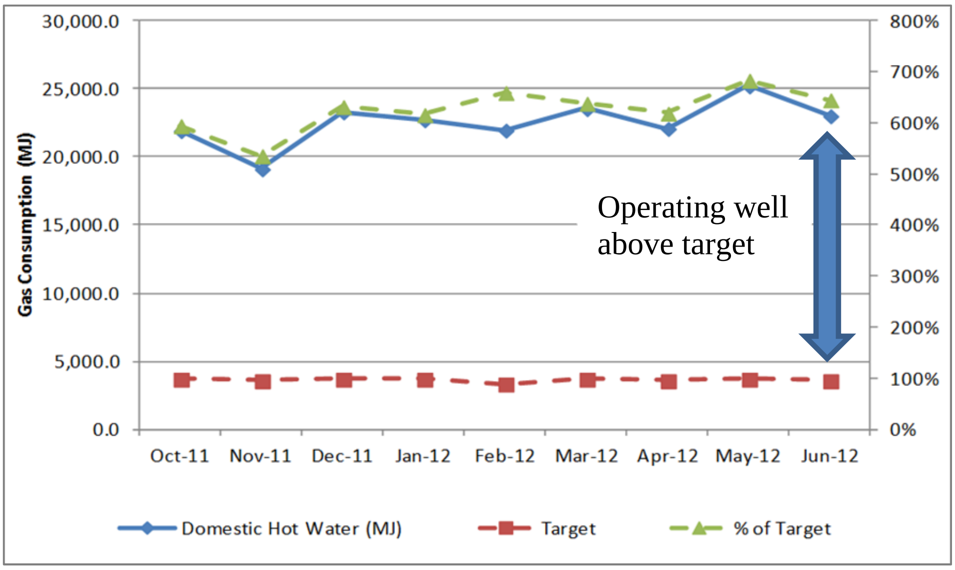

Fig. 9. Trend log of Domestic Hot Water energy consumption (Moffitt, Ardren, 2012)

The graphs above (Moffitt, Ardren, 2012) show that after the initial "bedding down" period, all major systems are tracking very close to target performance parameters. However, Figure 7 shows that the Domestic Hot Water energy (gas) consumption, while small in comparison to other systems, was excessive and needed to be addressed. (Turning off the circulating loop at night and over weekends)

In addition to the monthly energy and water consumption reviews, quarterly operational reviews of the various mechanical systems performance in terms of functionality, hours of operation and achievement of thermal comfort conditions have occurred. The initial phase of these operational reviews consisted of investigation on site of anomalies found in the trend logs and issues raised by the occupants. This was followed with face to face meetings with the tuning team and occupant representatives in order to agree on remedial actions. An action list was issued to relevant sub-contractors and followed up by the team leader.

After implementation of the agreed remedial actions, independent verification was undertaken to confirm that the action had the desired effect. Thus, completing the feedback loop.

7. Evaluation of process under Soft Landings framework and core principles

While this project was not carried out from the outset as a soft landings project, once the commissioning managers were engaged, the Soft Landings concept of a smooth and informed transition and follow up after handover were put in place.

The purpose of this evaluation is not to prove or disprove the Soft Landings framework, but rather to test which elements were demonstrated to be absolutely essential and also to confirm if the majority of the benefits can be realized if the project did not follow the framework and principles from commencement.

Table 1: Evaluation against Soft Landings framework and principles

Item	Framework and core principle	Applied Yes/No	Effectiveness
1	Adopt the entire Soft Landings process from commencement. Be explicit in implementation through all 5 stages	No	Our observation is that it is essential to be brought in to play before commissioning planning begins. Earlier is preferable, but maybe not as critical
2	Provide leadership and have champions for Client and Contractor. Engender trust and open/honest collaboration	Yes	Clear leadership definitely helped the team embrace and focus on performance outcomes. While there was a bit of a "contractual" mindset overshadowing completion, in terms of demonstrating operation of systems, all parties had a "no blame" attitude and "pulled together" to make sure it all worked correctly and efficiently
3	Set roles and responsibilities for all stages and ensure continuity. Active participation of client/owner and occupant representative	Yes	Initially role definitions were unclear and resulted in a lack of ownership of outcomes and poor progress. As leadership was established (and accepted), the focus on outcomes improved dramatically. The same leadership continued through into the post-handover stage and is still making sure tuning activities are correctly identified and implemented. Continuity of performance intent is essential from construction to occupation and operations
4	Ensure continuity of Soft Landings thread throughout the entire project	No	As noted above, a successful outcome has been achieved, even though the initial stages of the project did not focus on the performance outcomes Our observations would indicate that there is a person nominated to be responsible for carrying the continuity of intent through from one stage to the next.

Item	Framework and core principle	Applied Yes/No	Effectiveness
5	Commitment to post Practical Completion "aftercare" for 3 years with continuous feedback in place	Yes	Both the Contractor and Owner have committed to post-completion tuning and monitoring "aftercare". This has proven to be critical to the achievement of the target performance Having a structured and planned tuning process and regular measurement/reporting of energy use against targets has ensured that remedial actions are carried out in a timely manner, allowing for earliest possible rating of performance
6	Share risk and responsibility in a collaborative "no blame" approach	Yes	Since there was no contractual obligation for the construction team to achieve the performance outcomes, sharing of risk was practiced. In addition, given the initial design failings and lack of participation by the design engineers, there was a collaborative mindset to resolving design issues. This "no blame" mindset definitely contributed to the willingness of parties to contribute and collaborate.
7	Use feedback and surveys to inform design	Yes	Feedback and contribution of ideas and experience from previous projects had a big role to play in the success of this project. Lessons learnt by the commissioning and tuning teams have already been brought to bear on performance improvement and on other recent projects. Occupant observations and feedback have had significant input into the resolution of issues and identification of energy efficiency opportunities However, lack of participation by the design engineers in the construction and commissioning stages, has prevented them from incorporating these lessons in future designs.

Item	Framework and core principle	Applied Yes/No	Effectiveness
8	Focus on operational outcomes in-use and refine targets	Yes	The continuous focus and attention to in-use performance outcomes has unquestionably contributed to the success of the outcomes to date. Regular tracking and monitoring of energy use against target has been essential in maintaining focus. Targets are expected to be reviewed and refined after the first 12 months of operation
9	Involvement of Building Manager and maintenance crew	Yes	Early involvement of the Building manager and maintenance crews, prior to commissioning provided substantial value to the process. Both in streamlining the training process, and in the identification of time-based efficiency opportunities.
10	Involve end-users in all stages of the project	Yes	Early involvement ensured that the occupants were able to operate the building efficiently in record time. A Building Users guide was developed that specifically addressed operation from the perspective of occupants. In addition, customised “Quick reference” cheat sheets were produced and placed above each piece of equipment. As noted, direct feedback from occupants, while difficult due to security restrictions has been crucial in the identification of efficiency opportunities in the work spaces
11	Set realistic performance objectives	Yes	In Australia, the NABERS rating scheme provides a realistic industry benchmark. This allows for the identification of achievable performance goals. NABERS covers energy (emissions), water and waste – for the base building

Item	Framework and core principle	Applied Yes/No	Effectiveness
			services and for tenancy spaces. All monitoring and measurement is carried out following strict protocols against these standard benchmarks.
12	Communication and information sharing between all parties over each stage	Yes	Regular and open communication in terms of expected outcomes and required activities played a major part in the finalisation of the commissioning and handover processes. During the latter part of the12 months of "aftercare" to date, communication has diminished and as a result remedial works and performance improvements are lagging behind.

Fig. 10. "A" Grade office spaces and amenities

8. Conclusions

Contrary to indications and expectations of failure during the final stages of construction, concerted and focussed effort and attention has delivered a performance outcome that exceeds industry experiences and timelines.

Application of the majority of the Soft Landings core principles and some additional elements and procedures has demonstrated that industry best practice outcomes can be achieved in a timely manner without compromising operational function and thermal comfort.

While this project did not explicitly follow the Soft Landings framework, it has confirmed that the core principles carry substantial benefit when applied diligently and there are potentially a few additional practices that could be adopted into the framework. These include:

- more structured in-depth analysis of system operations prior to hand-over
- clearer planning requirements for the tuning process
- defining the Soft Landings lead role that is continuous through-out all stages
- requiring an element of active independent verification of commissioning planning and execution
- defining the scope and how to procure services post 12 months DLP
- defining the need for post-occupancy training and coaching for occupants and maintainers

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Strategies for smart building realisation

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Abstract:
Smart buildings as a concept is now becoming prominent in the vocabulary of Architects, Engineers, Construction contractors, Technology companies, Property developers and the Estate or facility management function within organisations. Public or private sector, smart building goals are now prevalent in corporate strategies whenever new build or retrofit / refurbishment is planned.

But there seems no common consensus on what this really means. The 1990's and 2000's witnessed much hype around intelligent buildings concepts. However in many instances the hype never produced tangible results. Now the scene has changed. Sustainability and carbon management is increasingly on the agenda of boardroom decision making and "smart" in smart buildings seems to have a purpose, almost as a mission statement.

The lack of clear definitions on what encompasses a smart building and what is to be expected when utilising a smart building whether as a solitary or group experience is causing the supply side industry to throttle back the adoption rate. Value structures justifying adoption are not clear in this early adaptor stage. Thus costs associated with the realisation of a smart building are quite hard to justify. This is compounded by the rapid pace of technology advancement and the continual refresh of new products and solutions that purport to provide an improved functionality or better price to performance advantage.

Thus strategies for smart building realisation need to be formalised into industry accepted frameworks which can be applied in many market sectors – or verticals, and which can be applied in the context of small, medium and large buildings or campus premises. This paper presents some thought leadership in this emerging area of expertise and provides concepts that may form the fundamentals for a future framework.

The author provides a perspective as a professional in Consulting for the Engineering and Construction industry with regards to integrating ICT systems into the built environment. ICT infrastructure comprises much of the building blocks for smart building enablement alongside automation and controls, electronic security and facility management applications. Converged IP networks, integrated command and control rooms, utility (smart) metering and integrated BMS (iBMS) enables smart building functionalities to be implemented. This paper presents viewpoints across all of these subject areas in the context of policies, technologies and obstacles.

Keywords:
Smart, buildings, master systems integrator, procurement.

1. Overview

There has been a lot of interest, investment and initiatives in the field of smart building, aka intelligent building, functionalities within the construction and technology sectors in recent times. Property developers, building owners, design and engineering consultants, facilities managers, product or system vendors, and some managed service providers have all invested in this area of work and now this community is effectively a stakeholder offering value added products and services for commercial returns.

The apparent lack in understanding or appreciation of the value structures that frame the concepts for smart buildings has seeded the need for further debate. This paper is intended to promote further debate within the end user and practitioner community with regards to some of the challenges in the whole procurement cycle from early conceptualisation, requirements validation, scoping and subsequent design, construction, commissioning and operational readiness.

Smart buildings realisation ultimately has to exist within the established protocols surrounding design and construction, which on the surface is easily achieved. However the growing dependencies between traditional Mechanical Electrical and Public health systems and business facing ICT together with associated specialist trades such as electronic security, audio visual and multimedia, building automation and control systems provides an additional layer of complexity which if unmanaged introduces new risks to design, assurance, performance and operation.

Ultimately, all the stakeholders involved will aspire to successful outcomes that delivers value add, high availability and reliability (Smith, 2002). This will invariably mean a joined up and co-operative approach across trades – a challenge for the industry which has a bias to conservative methodologies and silo based work practices for specialist trades.

2. What is a smart building?

The very clear and a certain point of principle is that buildings are form and function oriented, meaning that various market sectors will have certain bespoke and generic concepts for a building.

For example in the manufacturing sector, buildings offering office accommodation adjacent to a production facility will have some characteristics suited for the function which would not be found in a city centre professional services office building. This could be as simple as having a low cost approach to the shell or interior of the building, or a design that is demountable or transportable within a manufacturing facility.

In contrast an office building in a city centre intended for multi-tenancy with a target market in the professional services sector may well have attributes of a plush interior and will need to focus on user comfort and convenience.

Achieving a common consensus across all markets for what ‘smart’ means will therefore be difficult unless of course one has a more holistic view and somewhat generic attitude to broaden the definition.

Today such a holistic and generic definition may centre on themes of efficiency, sustainability or rich experience (CABA, 2008). Efficiency may be with building operations or business functions, sustainability could associate with energy or materials, and a rich experience could associate with service delivery.

This paper proposes that such thematic thinking needs to be embraced within the vocabulary of design professionals, clients and supply side contractors. Without such a guiding framework, the plethora of use-cases that could fall under the 'smart' definition could be so wide as to cause a high degree of fuzziness in the value propositions being put forward within a business case to justify investment in the realisation of 'smart'.

In simple terms then a "smart building" could be described as one which is responsive to the functional needs of its occupants, and is efficient and effective from a total cost of ownership view. In this regard cost of ownership could be owner/occupier facing direct costs or a tenancy leasehold with associated service and utility charges. A smart building may also be characterised as having relatively lower depreciation or comparatively higher appreciation in asset values over time in relation to other adjacent or similar structures with comparable uses. Thus a smart building will exhibit traits of higher market and/or balance sheet attractiveness.

3. Why need a smart building?

This is quite a philosophical question to ask. However it is a highly relevant question in the modern context. Many businesses looking to invest in owner/occupier building(s) and those in property development and real estate who are looking to profit from construction of speculative structures will at some stage contemplate such a question.

In the past the smart / intelligent building 'label' had origins in marketing attractiveness or corporate 'branding' needs as a way to demonstrate a unique differentiator. Sometimes this led to gimmicks of technology 'bling' or 'technology for technology sake' investments without any tangible business workflow drivers. In other instances investments in 'iconic' form and geometry was also associated with 'smart' realisation, and led to creative structures either loved or hated depending on the viewpoint of the observer. For example fanciful facade structures offering a utility value were the result of such intervention.

In other instances, simple integration, or common use systems – such as a shared cable system or shared data network (aka converged IP network) were touted as signs of smartness and even intelligence. The 1990s for example had many examples of such embryonic thinking and realisation. In recent times there has also been a simplistic interpretation that a unified building management system computing front end is the manifestation of a smart building. We do need to ask ourselves "Is that the be-all and end-all of smart building realisation?"

Today the need for a smart building is characterised by the following drivers:

- Ability to demonstrate sustainability interventions – for example to be energy efficient in operations and/or in design and construction, and to have a means of measuring and monitoring in real time the utility consumption data to make continual improvements to carbon footprint (Sinopoli, 2012)
- Business responsiveness to modern work ethics – for example to allow formal and informal meetings in the right ambiance, improved user comfort and conveniences, flexitime working and hot-desk working, and a work anytime, anywhere concept

where a unified computing workplace, i.e. the computing desk-top is THE workstation, where the physical surface is just an ancillary necessity

- Outsourcing of non-core support functions – for example a smart building could encourage outsourcing the building maintenance, facility management, catering, IT support and security functions, which in some instances may necessitate a partial devolution of responsibility with regards to building management decisions to a 3rd party
- Agility for change in business operations – for example to respond rapidly to an expansion or downsizing plan – such as how quickly can a floor or part building be sub-let or how quickly can the business relocate with minimal property related costs?

Thus the degree of smartness and corresponding scale of investment (and thus smart interventions at the design stages) has a wide catchment definition for acceptable realisation depending on end user focus on any one or more of the above drivers.

Thus one of the early actions – whenever formulating a building brief – is to strategise focus areas in relation to the above drivers. The building brief to an architect-engineer design team should then be clear in terms of 'smart' expectation or requirements. Where necessary such activity may be supported by professional advice from technology consultants and building performance engineers.

4. Smart building design brief

The absence of a formative template for structuring a brief which could provide the subliminal comfort of industry acceptance and recognition, and the absence of generic standards is a real hindrance to the process of smart building realisation. Whereas in traditional engineering such templates exist for Mechanical, Electrical and Public health requirements, there are no real equivalents for ICT and other specialist trades such as Audio Visual, Multimedia, Electronic Security and Building automation, controls and management that are cornerstone to smart buildings realisation. Often this seems to arise from the construction industry as a whole, deferring decisions for such systems to the 'very last responsible moment' in their design and procurement process, so as to focus on form, function and structure early in the design stage. This can be quite detrimental to smart building realisation since it means that any consideration of 'design for operations' is absent in a building brief.

So what should be or could be in a design brief, and how can we get as close as possible to communicating requirements accurately and timely?

To be effective in practice, a smart building design brief needs to focus on the key areas of:

- **Life expectancy** for the building in terms of a short and long term profile, with a set of recommendations regarding expectations of technology longevity/refresh cycles in all building engineering disciplines – from MEP, facades, fire, acoustics, lighting, vertical transportation, ICT, audio visual, electronic security, automation & controls and FM and logistics. Thus one would expect guidance on major refurbishment cycles and how this would impact on mainstream and specialist disciplines
- **Concept of operations** for the business and the building, in an owner-occupier model, and a concept of operations for just the building in a speculative multi-tenancy type building. Thus one would expect guidance on the workflow dependent

technology aids, decision support systems enablement (such as alarm management, incident management, metering and performance monitoring policies) and KPIs which could also include targets such as carbon emissions

- **User centric experience** for key occupant profiles, from support staff to production workers or visiting guests whether in the knowledge economy or in other mainstream functions such as manufacturing, science or research. Thus one would expect guidance on the level of richness required in the user experience and how the building ambiance and interior, the engineering and technology systems and ergonomics of furniture fittings and equipment will need to be supportive of the set objective(s).
- **Procurement methods and supply chain** management with guidance on how responsibilities are managed during the entire lifecycle of design, construction, commissioning, fit-out and occupation. For example smart building realisation may warrant extended assurances for engineering continuity across a ‘practical completion’ milestone as a ‘hard stop date’ in contract, which if not planned for in advance could become a particular problem later. Early guidance on how fit-out activity aligns with a business facing operational readiness and service activation process in the lead up to occupation will be of value during the planning and construction phases of a building project. Where smart building realisation is enabled using particular software applications which have engineering dependencies across contracting boundaries, early definitions for how this will be managed is highly valuable to mitigate technical and administrative risks and manage/contain costs.
- **Value management** for smart building realisation with guidance on how costs are managed as a whole, where direct costs for engineering assets and systems are compared with opportunistic savings from a smart building realisation; for example reduced man-power in maintenance activities, savings from common/shared assets and integrated spaces and efficiencies in energy consumption should form part of the overall cost model; a smart building realisation should ideally not have a net uplift in construction costs, and a value management statement should outline how this should be achieved, prior to a RIBA stage C or an AIA concept commencing.

Historically investment in a smart building brief is seldom found at a RIBA stage A, B or C or equivalent AIA design stages. This has been a contributory cause towards under delivery on ‘smart’ ambitions set by the client and for being one of the first items to be value engineered out whenever budgets are under pressure – i.e. it is hardly considered to be a must-have non negotiable item.

Thus the availability of a smart building design brief at early feasibility and planning stages which forms part of a design brief to the architect will mitigate some of the risks causing under delivery on many construction projects. In fact at the feasibility stage there needs to be due diligence analysis to align smart objectives with a well rounded technology vision and a technology Masterplan. Why you may ask, the simple answer being that many construction projects tend to have a long incubation period, and timelines of 3 to 7 years are not uncommon. Technology advances in industry are constantly encouraging rapid obsolescence and mature or proven concepts of the day may well be out-of-date by the time a building is ready for fit-out and occupation. This should however not be a barrier towards any form of investment in technology, but it should encourage a means to manage technology deployment, investment budgets and procurement strategies using a custom project governance policy and procedure that is understood by all stakeholders.

5. Prioritisation of objectives

A strategy for smart building realisation needs to consider the issue of prioritisation of requirements associated with ‘smart’ objectives. The ownership of the ‘smart’ objectives customarily is not clear cut – between the estates function, the IT function and the business administration function. Thus it is common for a brief to be a collection of wish-list items with no positive attributable ownership or priority. Moreover business case justifications for wish list objectives are absent or fuzzy in a typical smart building brief which usually causes design team stakeholders, mainly project managers and cost consultants, to begin questioning or challenging the brief.

Prioritisation is a necessary part of the strategy for smart building realisation. To do this effectively one needs to have a CFO / CEO perspective of the business – such as its outlook, core values, near and long term ambitions, and appetite for specific investments in ‘smart’ objectives that support specific causes; for example sustainability initiatives, CSR, regulatory compliance, and monetisation of infrastructure and facilities (such as renting out meeting and conference spaces or subletting excess floor space).

This paper proposes that prioritisation should always be a client function and never delegated to a design team, although a design team or specialist technology consultant may contribute to the prioritisation and decision making processes. Thus at the feasibility stage a design brief should ideally provide guidance on the prioritisation of requirements falling within the ‘smart’ objectives.

One of the safeguards that assures continuity of intent during the project lifecycle from early inception to final occupation is the knowledge of available budget for each of the smart objectives, or at the very least a headline budget for the ‘smart’ brief. Should this budget allocation effectively be a positive sum or zero sum calculation within the whole project is one question which needs to be carefully thought out at the feasibility stage. For example a zero sum calculation is where existing budget allocations across various trades are ‘taxed’ to create a new budget for smart objectives, and a positive sum calculation offers new budget to add to the planned budget. For example a positive sum may be justified on the basis of added property value or kudos associated with a differentiator. There could also be a halfway house where planned budgets are taxed (to a lesser degree) and some new money is allocated for ‘smart’ objectives.

6. Functional use cases

Smart objectives may become fuzzy within a governance structure where requirements are headlines only with little detail. Functional use-cases may be developed for each of the desired smart objectives to illustrate what is actually to be achieved. The importance of elaboration of use cases is the ability for wider communication of business intent and its dependencies with the built environment, interior design, furniture, fittings and equipment and the impact if any to existing workflows in relation to core business activity or support functions. This is often quite important at a planning and concept stage of architectural design since space allocations and related parameters are set during a RIBA stage C.

Typically functional use cases tend to converge around headline themes such as:

- Enhancements to visitor/guest services

- Operational enhancements to estate and facility management workflow
- Co-ordinated incident management and decision support systems with interfaces to fire systems, security systems, ICT and building controls and automation
- Unified service desks across support functions such as ICT, AV, Facility management and Security
- Metering and sub-metering
- Automation in facility reservation systems
- Energy management policies
- Building performance dashboards and digital signage systems
- Orientation and way finding aids
- Unified identity management, one-card access, cashless transactions

Other themes specific to a sector, such as rail or air transportation, are likely to arise and should be included where relevant.

7. Planning for implementation

Smart building objectives invariably cut across a number of building trades. In recent times many ICT contractors, mainly system integration companies, have taken the mantle to deliver smart objectives. In other instances building automation and controls companies have been the prime contractor for this work, and often they are referred to as a 'master systems integrator', or MSI.

The procurement of such services is not as straightforward as some might wish. Often issues of timing, contractual interfaces and responsibilities, handover milestones and related critical path dependencies make the process of managing the implementation quite a complex task. Competencies around smart building realisation within general contracting is not yet mature, and finding human resources with the experience and skills to deliver efficiently is still a challenge.

Thus an essential component forming the strategies for smart building realisation is the presence of a joined up procurement strategy that finds the path of least resistance within the supplier/contractor community. The procurement strategy should also consider if responsibility for performance and functionality can be continuous from time of installation through testing and commissioning and early stages of live operations (i.e. the transition to service activation). Often this may need strategic foresight in the decision making process to select a vendor capable of offering services beyond the practical completion of a construction contract, where obligations are clearly bounded but not discontinuous across the hard-stop date of a practical completion and subsequent defects management period. The obvious risk that needs to be managed is that a contractor who is construction facing may have no interest in how the systems perform in real life even though 'smart' objectives will be based on the promise of workflow or energy management related benefits which are closely linked to the internal working procedures of a business organisation. Thus a basic reliance on standard warrantees and guarantees for materials or workmanship may not be enough.

One means of mitigating risks associated with the procurement is the availability of competent professional services during the design and tendering stages of a project, which is able to represents the interests of the 'smart' objectives in the design team. Creating a specialist package of work that articulates the 'suite' of smart requirements using contract language, technical standards and KPIs which can be verified at set milestones is a specific output that should be delivered by a smart buildings consultant. Industry experience suggests risks may be better managed by way of traditional design team engineers, architects and specialist consultants working for a client/owner directly rather than as part of a design and build contracting team. One reason for such assertion is that the budget holder for smart objectives will be the client at least until a systems design is developed and ratified, whereas in design and build budget control passes to a prime contractor, who may opt to shift budget priorities to manage commercial interests and project outcomes to own agenda. The other reason being that within traditional design teams, a client may have more flexibility to introduce refinement or change to smart building objectives with lower resistance than within a design and build type contract.

8. Wider implications of the proposed strategies

There are many practical and pertinent implications arising from the strategies proposed in this paper. First and foremost, there needs to be acceptance in the construction industry, architectural community and within corporate sponsors of new projects, the growing necessity to include ‘smart’ aspirations in support of sustainability and building performance objectives. This will result in system requirements being mandatory rather than just a “nice to have”. The reason being that, energy and carbon management of the built asset has a growing prominence and is being mandated. Add to this the unspoken or unpublished expectation of business executives for process efficiency aided by a smart building environment.

Secondly there needs to be a greater role for design and consulting engineers in the buildings industry with specialist skills, such as building automation and controls, building operations and logistics and ICT infrastructure, to define performance and functional requirements, well ahead of time. This is alien to the hitherto customary practice of specialist input mid stream in a RIBA or AIA design process. Why, one may ask. The high impact objectives in relation to both the building and the business operational requirements need to influence the design brief for a smart building. Thus, to deliver a smart building with utility value, a considered view of multiples of operational requirements is needed with harmonised inter-relationships. The financial implications (e.g. cap-ex /op-ex) of a smart building need to be assessed at the feasibility stage and a brief generated for an architectural design. For example a wireless and radio friendly building will have requirements in relation to specifications for building materials, facade, interior partitions and an intelligent or active facade solution may have requirements that will not fully align with the former. Equally support contracts for traditional FM functions may not align with a newly acquired smart building. Furthermore, a converged IP network supporting building operations may not align with business requirements for high availability or information security. The outcomes of a requirements analysis and the resulting ‘project plan’ for a smart building/estate will almost certainly influence the form and functional requirements for any building in any sector, small, large or in very large campus construction. The close coupling of building performance aspirations with business work flow efficiency, and the need to collate, process and display various management information KPIs, together with the ubiquity of Ethernet/IP networks in building automation and security systems justifies early input from specialists in ICT infrastructure and information systems.

Thirdly, the construction industry together with the ecosystem of suppliers to the buildings trade need to actively take steps to embrace smart building aspirations even if it means traditional boundaries and responsibility lines need to be reshaped. This may well need new supportive education oriented information dissemination for continual professional development.

9. Conclusion

Smart buildings realisation is a specialist area of work. There are particular risks to realisation; however the rewards of delivering a true smart building may outweigh potential for disruption from inherent risks. Managing the risks during design and later implementation requires professional expertise, especially if in house technologists and engineers lack experience in this area.

Smart building functionalities are here to stay and will increasingly take on a more prominent role as the ubiquity of anytime-anywhere access to information and knowledge sources becomes more prevalent. ICT tools, mainly end point devices such as the new generation of internet connected tablets and ultra books, and newer generation of AV aids will create opportunities for new applications to emerge offering unified portals to manage the work place, work area and work station. It is likely that many work places will in the future need to offer a richer experience to its occupants, simplify support procedures to reduce overheads in property and estate, and provide demonstrable sustainability initiatives through smart interventions in design, construction and operations.

Factoring smart building realisation as part of new build or major refurbishment will therefore be top of the list of priorities of many project sponsors.

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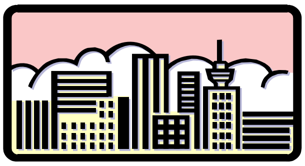

Fig. 1. Figure text below the figure (Figure Caption)

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Social and Economic Challenges of Implementing Sustainable Materials on Buildings in Kuwait

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Abstract

Many factors affect attaining the required credits for LEED materials and resources (MR) section. There are disadvantages in obtaining credits and LEED certifying an existing building in Kuwait to become a sustainable green building. LEED is still relatively new in Kuwait and the Gulf region, therefore, when certifying an existing governmental building, difficultly is faced with obtaining complete building owners, building upper management and occupant cooperation. This raises challenges when requiring cooperation from building occupants and cleaning staff for the solid waste management credits which require dedication to reduce the amount of waste going to landfills and incinerating facilities. The mindset of the contractor and subcontractor has to change to gain full understanding and cooperation in the waste management of construction materials when constructing new buildings and performing facility alterations on site. The selection of sustainable materials is more challenging as many materials are not available in Kuwait and the surrounding Gulf countries. Transportation from aboard should be decreased as much as possible to reduce cost as well as decreasing negative environmental impacts. Green certified materials are more expensive, therefore decision maker have to be willing to pay the extra cost.

This paper discusses the challenges faced by KISR team as a consultancy body to certify an existing building according to LEED rating system from the material and resources aspect. It discusses the acceptance of the building owners, building upper management and the building occupants to this change and their understanding and cooperation. Many materials for MR credits 2 and 3 were found difficult to be obtained in Kuwait and the surrounding gulf region. Some materials were found to be available in the

Gulf region. Each credit will be examined, the challenges KISR staff faced and the means they were overcome.

Keywords:
credits, environmental impacts, existing building, facility alterations, incinerating facilities, LEED, material and resources (MR), solid waste, sustainable.

Introduction

The LEED green building rating system, which stands for Leadership in Energy and Environmental Design, was established in 1998 by the US Green Building Council (USGBC). LEED was designed to promote design and construction practices that reduce energy consumption, gas emissions and improve occupant health. USGBC administers the development and ongoing improvement of the LEED rating systems and is also the primary source for LEED and green building education and resources for project teams. USGBC’s mission is to promote the design and construction of buildings that are environmentally responsible, profitable and healthy places to live and work. The Green Building Certification Institute, (GBCI), which was established in 2008, administers and awards LEED certification to all commercial and industrial projects registered under any LEED Rating System. The report “Green Building by the Numbers”, published in April 2009 by USGBC “states there are 2,476 LEED certified projects and 19,524 registered projects, distributed in over 90 countries.” Altogether, commercial building space with LEED certification amounts to more than 5 billion square feet. LEED is a relatively new practice in Kuwait and has only been adopted during the past couple of years, therefore implementing LEED on new and existing buildings is extremely challenging. In this paper we will discuss the challenges faced by the project team, and how they were overcome while implementing LEED Existing Building Operations and Maintenance (EB O&M), Material and Resources credits on an existing building in Kuwait. Building owners and decision makers in Kuwait have to understand the advantages of adopting LEED. A green building will reduce the negative environmental impacts of different materials brought into the project building. LEED will also reduce the impacts of consumption of electricity and water which will be of a great benefit to Kuwait as it is considered one of the highest countries in electrical power and water consumption. The peak electrical load reached in 2012 was 11,850MW and according to 2011 statistics each person in Kuwait consumes 600L of water a day. By implementing LEED we hope these figures will significantly decrease. There will be economic benefits from an obvious decrease in operating costs and increased productivity. The community will benefit by minimizing the strain on local infrastructures, hence improving the quality of life. It will enhance occupant comfort and health. Adoption of LEED requirements in office buildings will provide employees with a healthy and comfortable workplace, leading to employee satisfaction. It will improve occupant performance, and in turn will reduce absenteeism and turnover, which will decrease productivity losses per year.

There are different LEED rating systems for different types of buildings. Table. 1 shows the various rating systems and their reference.

Table 1. LEED Rating System.

Rating System	**Reference Guide**
LEED for New Construction	GREEN BUILDING DESIGN &CONSTRUCTION 2009 Edition
LEED for Core & Shell	
LEED for Schools	
LEED for Healthcare	
LEED for Retail	
LEED for Commercial Interiors	GREEN INTERIOR DESIGN & CONSTRUCTION, 2009 Edition
LEED for Retail Interiors	
LEED for Existing Buildings	GREEN BUILDING OPERATIONS & MAINTANANCE, 2009 Edition
LEED for Existing Schools	

LEED Existing Building Operation and Maintenance Rating System

LEED for Existing Building Operation & Maintenance (EB O&M) rating system helps building owners and operators measure operations, improvements and maintenance on a consistent scale, with the goal of maximizing operational efficiency while minimizing environmental impacts. It addresses whole-building cleaning and maintenance issues, including chemical use, recycling programs, exterior maintenance programs, and systems upgrades. LEED EB O&M certification is granted by GBCI for projects when sufficient documentation proves compliance with the required number of prerequisites and optional credits. LEED EB O&M will transform the way buildings are operated enabling an environmentally and socially responsible, healthy and prosperous environment that improves the quality of life. It aims to minimize the landfill and disposal of different materials brought out of the project building and to greatly reduce operating costs. LEED EB O&M will transform the way buildings are operated enabling an environmentally and socially responsible, healthy and prosperous environment that improves the quality of life.

There is currently no LEED EB O&M certified building in Kuwait however there are two LEED EB O&M registered buildings. There is one LEED EB O&M certified building in Dubai, the Dubai Chamber of Commerce and Industry which is also the only one in the Arab World. Based on 2010/2011 studies, outside of the USA there are only 12 LEED EB O&M certified buildings.

To gain certification, points must be earned. There are Minimum Project Requirements (MPR) and prerequisites, which are mandatory requirements and vary according to each rating system. These must be met in order for the project to achieve LEED certification. Then there are selective credits, which are non-mandatory and comprise of points. These credits are chosen by the project team according to their preference to achieve score points. A minimum of 40 points should be earned to gain certification.

The Minimum Project Requirement for LEED EB O&M is the same for every LEED rating system and is as follows:

1. The project must comply with environmental laws.

2. The project must be a complete, permanent building or space.

3. It must use a reasonable boundary.

4. The project must comply with minimum floor area requirements (93 m^2 gross floor area).

5. It must comply with minimum occupancy rates where Full Time Equivalent occupancy (FTE): one or more FTE and Minimum Occupancy Rate is twelve consecutive months.

6. The project must commit to sharing whole-building water and energy usage data.

7. It must comply with a minimum building area to site ratio (no less than 2%).

EB O&M certification is granted by the GBCI for projects when sufficient documentation proves compliance with the required number of prerequisites and optional credits that are distributed between seven categories; Sustainable Sites, Water Efficiency, Energy and Atmosphere, Materials and Resources, Indoor Environmental Quality, Innovation in Operation, Regional Priority.Certification is awarded based on the number of points earned.

EB O&M Materials and Resources Credits (MR)

The intent of this Credit as stated in LEED 2009 for Existing Buildings Operations and Maintenance is "to reduce the environmental and air quality impacts of the materials acquired for use in the operations maintenance of buildings". Its goal is to reduce the negative environmental impacts of different materials brought into the building and to minimize the landfill and disposal of different materials brought out of the building. Adopting a sustainable building will reduce waste by managing waste solids, it will focus on reusing and recycling materials whenever possible. Mercury pollution generated in the building will also be reduced. Adopting a purchasing program of green sustainable materials as well as managing waste solids can achieve these objectives. Material and Resources credits are described below:

- MR Prerequisite 1: Sustainable Purchasing Policy (Required)
- MR Prerequisite 2: Solid Waste Management Policy (Required)
- MR Credit 1: Sustainable Purchasing- Ongoing Consumables
- MR Credit 2: Sustainable Purchasing-Durable Goods

- MR Credit 3: Sustainable Purchasing-Faculty Alterations and Additions
- MR Credit 4: Sustainable Purchasing-Reduced Mercury in Lamps
- MR Credit 5: Sustainable Purchasing-Food
- MR Credit 6: Solid Waste Management-Waste Stream Audit
- MR Credit 7: Solid Waste Management- Ongoing Consumables
- MR Credit 8: Solid Waste Management-Durable Goods
- MR Credit 9:Solid Waste Management-Facility Alterations and Additions

This paper is mainly about the obstacles and challenges faced economically and socially during the implementation period for different credits within the materials and resources category for an existing building in Kuwait. The first section discusses obstacles and difficulties faced in Kuwait with regard to sustainable purchases, while the second section discusses the challenges related to waste management.

Section 1: Sustainable Purchasing

This section will discuss the material and resources prerequisites and credits for LEED EB O&M and how they were tackled and overcome by the project team.

When purchasing sustainable environmental friendly products, the following issues have to be considered:

1. There should be a reduction in the use of resources.
2. There should be a reduction and prevention in waste produced.
3. Occupant’s health and safety should be taken into consideration.
4. The growth of a sustainable economy.
5. Pollution and toxin reduction.
6. A reduction of greenhouse gas emissions.

Sustainability requirements for some of the MR credits were found to be applicable in Kuwait, on the other hand, challenges were faced when applying sustainable measures to some of the MR credits. The difficulties faced can be generally described as :

- Limited choices of sustainable materials in the local market.
- Limited number of vendors locally or in the Gulf region.
- Lack of cooperation with vendors .

- High cost of available sustainable materials in the local market.

To certify an existing building as a green building according to LEED requirements, at least 60% of the purchases of ongoing consumables (MRC1) should fall within the sustainability criteria specified below:

- Materials harvested and processed or extracted and processed within (800 KM) of the project.
- FSC certified paper
- Rapidly renewable materials such as bamboo, cotton, cork and wool.
- Rechargeable Batteries.
- Post-consumer materials and/or post-industrial materials.

The challenges faced while implementing this credit in Kuwait is that there is a limited availability (if any) of locally produced sustainable ongoing consumables. FSC paper is very difficult to find and if available is extremely expensive compared to the price of regular paper. Building owners or decision maker for office buildings still do not comprehend the importance of purchasing FSC paper. They also are still not aware of the significance of purchasing other sustainable materials at more expensive prices when to them; the same material is available for a less price. There are a limited number of vendors supplying sustainable consumable goods in the local market. It is possible to obtain materials containing pre or post consumer materials, but they do not contain the percentages specified by LEED. There is a lack of cooperation with some potential suppliers of sustainable consumable goods. As for MRC2, at least 40% of the purchased durable goods (electrical equipment and furniture) should be sustainable.The sustainable criteria for electrical equipment is energy star**.** Although energy star qualified equipment is widely available in the Kuwaiti market, they are not always used or purchased as they are much more expensive and to the building owners point of view are not attractive cost wise as electrical equipment with the same use and are not energy star qualified. This issue should be clearly clarified to building owners. Challenges are faced when employees are encouraged to minimize the number of printers and copiers in a building, and to share these machines, in order to reduce VOCs and provide a healthy working environment. There is not enough cooperation from the employees to perform this step as it requires changes in their regular daily routine which they are not inclined to take as they do not fully understand its benefits.

When furniture is to be purchased, the following criteria should be applied for at least 40% of the purchased goods:

- Materials harvested and processed or extracted and processed within (800 KM) of the project.
- FSC certified wood.
- Rapidly renewable material.
- Material salvaged from off-site or on-site.
- Post-consumer materials and/or post-industrial materials.

There are very few vendors that supply sustainable furniture in Kuwait therefore the designs and colors are very limited. There has to be a large order for sustainable furniture to make it worthwhile cost wise to order it from reliable vendors located abroad, however LEED encourages the use of local producers to decrease transportation costs and to reduce pollution from planes, ships and other transport vehicles that may be used to transport the furniture to Kuwait. Sustainable furniture is much more expensive than other furniture of which there is a wide variety of designs, material and colors, therefore building owner and decision makers have to be completely aware and dedicated to the purchasing of sustainable furniture.

Any alterations and additions for the building should satisfy LEED requirements for this credit (MRC 3) by at least 50% as follow:

1. Green seal’s standard GS-11 requirements for paints and coatings
2. Non carpet finished flooring are Floor Score-certified.
3. The carpets meets the requirements of the CRI Green Label Plus Testing Program.
4. Carpet cushion meets the requirements of the CRI Green Label testing Program.
5. Adhesives and sealants should have a VOC content less than the current VOC content limits of South Coast Air Quality Management District (SCAQMD) Rule # 1168, or sealants used as fillers must meet or exceed the requirements of the Bay Area Quality Management District Regulation 8, Rule 51.

6. Composite panels and agrifiber products should not contain any added urea-formaldehyde resins.
7. Forest Stewardship Council (FSC) certified wood.
8. Rapid renewable materials.

The selected materials should decrease the emission of harmful gases, volatile organic compounds (VOCs) to the environment, and therefore improve the general quality of surrounding air. Concentrations of many VOCs are consistently higher indoors (up to ten times higher) than outdoors. The adverse health effects of VOC exposure are they can cause eye, nose, throat irritations, headaches, loss of coordination, nausea, and damage to liver, kidney, and to the central nervous system. Some VOCs are suspected or known to cause cancer in humans. Key signs or symptoms associated with exposure to VOCs include:

- Conjunctival irritation (pinkeye)
- Nose and throat discomfort
- Headache
- Allergic skin reaction
- Nausea
- Fatigue
- Dizziness
- Shortness of breath which may lead to asthma & cardiac disorders

Psychologically, staff will not be comfortable working in an environment that may cause any of these symptoms and productivity will be low.

Kuwait is a relative new market for LEED certified materials, therefore difficulty is faced locating LEED materials required for this credit available locally and when found they will be more expensive therefore difficulty is faced is persuading upper management to purchase the material. Many LEED certified materials do not have a local supplier and problems are faced with upper management acceptance when requesting items with no locally supplier. Specifications for this credit are very difficult to find in the local market, at best can be found in the surrounding Middle Eastern countries or imported from aboard.

As mentioned earlier in LEED specifications, materials salvaged off-site, or materials salvaged on-site and refurbished building materials and products such as beams and posts, wood flooring and paneling, doors and frames, cabinetry and furniture, brick and other masonry products, hardware and lighting can be used for the building alterations and additions. To Kuwait this is a very new concept to use salvaged and refurbished materials for a new addition to any building and it is not easily accepted by building owners. The requirement that would be easiest to accomplish would be purchases harvested and processed or extracted and processed within 500 miles which can be purchases from the surrounding Middle East countries.

Maintaining a sustainable food purchasing program that satisfies purchasing of at least 25% of total combined food and beverage purchases (by cost) during the projects performance period of a project is essential to earn the point associated with this credit (MRC5), however, It is tough to obtain in Kuwait local market foods and beverages that bear the following food certifications required by LEED and if found they would be very expensive:

- United States Department of Agriculture (USDA) Organic
- Food Alliance Certified
- Rainforest Alliance Certified
- Protected Harvest Certified
- Fair Trade
- Marine Stewardship Council's Blue Eco- Label

To overcome this obstacle, 25% of food and beverages purchases by cost were selected from factories that are within 100 miles radius from the building location.

Section 2: Waste Management

Different types of waste recycling programs can be performed for an existing building during the building performance period, including recycling of consumables, durable goods which has a longer service life than the ongoing consumables and recycling of any construction waste generated after any renovation or construction work in the building. LEED encourages reuse and recycling of consumable materials when possible in order to reduce the landfill and protect the environment and public health, conserve natural resources, and reduce toxicity. This requires performing a waste stream audit for the waste generated from the building and according to the output of this audit a recycle and reuse program can be adopted. To successfully implement these credits (MRC6 and MRC7) in Kuwait, there should be complete cooperation and commitment from building owners, occupants and staff to the correct disposal of waste. They should be completely committed to recycle waste for the long term and not just for a short period of time while it is a novel and new idea to them. The recycling rate is derived by comparing the amount of consumables diverted from the landfill to those consumables sent to the landfill over a given time period. The building occupants have to reach this goal and recycling is still a new concept in Kuwait that many people are still not committed to. It is also difficult to locate local companies that will recycle or dispose of waste in a responsible manner.

In performing this task, the following challenges were faced:

- Lack of awareness and cooperation from housekeeping staff and building occupants with the audit team which requires sorting of the generated waste during the whole time of the audit period.
- Lack of commitment of the recycling party with audit team.
- No availability of a batteries recycling program.
- Lack of cooperation from building occupants in sorting wastes and dropping waste at the specified waste container.
- Lack of commitment from cleaning staff to transfer waste continuously from collection points in the building to the recycling area.

This task requires acceptance of building occupants to minimize waste as possible, as well as work or use recycled materials. In addition, regular continuous monitoring of the solid waste stream recycling program is required.

Another recycling program has to be adopted for durable goods in order to reduce waste from building occupants going to landfills or incinerators. A waste reduction and recycling program for durable goods that are replaced infrequently such as computers, monitors, copiers, printers, scanners and televisions should be established. 75% of the durable goods waste stream by weight, volume or replacement value during the performance period of a project should be reused or recycled. In Kuwait recycling is usually measured by volume. These items include:

- Office electronic equipment.
- Appliances.
- Power adapters
- Televisions and audiovisual equipment.

Durable goods should be separated from ongoing consumables. Bins designated for durable goods must be established and signs should identify the types of waste allowed. The amount of durable goods intended for landfills should be reduced. A formal reuse program for furniture and electronics has to be established. The reuse program can be achieved effortlessly in Kuwait by donating furniture and electronics to countless charities in the country, but it may be challenging to make the program formal where all the occupants dispose of their furniture and goods in one place and it will be sorted out by committed staff and donated to charities. Difficultly will also be faced in gaining cooperation from occupants, staff and janitors to dispose of durable goods in the correct allocated waste bins and to commit to it in the long run. It will be also challenging to establish a method to track and calculate all landfilled and diverted durable goods as required by LEED.

Construction and demolition waste needs to be recycled by keeping it out of landfills and reusing appropriate materials.

It will be challenging to create and use a waste management strategy for construction materials. Qualifying materials include those that are removed and reused. Cooperation from contractors is required as they should be willing to design with standard-sized materials and avoid waste from cutting materials to odd sizes. They should consider using bolts in place of glue, be willing to minimize waste on the site, such as by over packing and create a tracking program for all waste to ensure uncontrolled waste is not leaving the job site. Contractors and subcontractors should be oriented at the start of construction on how to manage waste, to control it and how to track all applicable waste materials generated and diverted**.** A quality-control program should be implemented to ensure diversion targets are being met. The contractor should designate recycling areas on the job site and make sure workers are aware of them and their functions. Usually uneducated workers are constructing on the site, therefore it will not be easy to get them to place the waste to be recycled in their designated bins. To achieve these goals, gaining complete cooperation from contractors is obligatory. The contractors have to be educated to want to enforce LEED and insist that all the laborers and construction staff on site perform the LEED requirements. It is also essential to find and work with a reliable waste hauler who will establish a system to manage and track construction waste, which is also not easy as there are very few dependable waste haulers in Kuwait. In addition, any generated construction waste is not easily transferred to be used in a different site by recycling companies here in Kuwait, as most of the recycling companies currently deal with specific types of waste such as paper, plastic and metal and have no interest in using construction waste. Only limited number of recycling companies in Kuwait deal with such type of waste, and only with large quantities.

Conclusion

For LEED to be implemented successfully in Kuwait, there has to be complete building management and building occupant cooperation. All people involved with the building have to be dedicated to making a change and want to achieve a green building. The general mindset, awareness and dedication of the public should be changed to make more people care about the environment and the future and be more involved. Applying LEED requirements to an existing building in Kuwait is challenging but possible if buildings owners and occupants are willing to cooperate and abandon some of their habits to their daily routine in order to work for a healthier and safer environment.

In Kuwait, the price of electricity is very low as it is subsidized by the government, so the general public and building owners do not really have any incentive to lower their electricity bill which will be one of the perks gained from having a LEED certified building. However, company employers and building owners could provide mandatory workshop to new employees and new building tenants to educate them on the benefits of sustainable practices to their self, their families and the environment. The Kuwaiti government could encourage vendors in the local market to provide good quality environmentally friendly goods that satisfy green building requirements by providing them with extra privileges and incentives which will ease and smoothen importing of such goods to Kuwait. More attention should be given to the recycling issues in Kuwait by enforcing properties owners to sort the waste, therefore easing the recycling process for both building owners and recycling companies.

The Kuwait Green Building Council was established in March 2012. Their purpose is to encourage sustainable buildings by showing the positive effects on climate protection, resource consumption, health, quality and efficiency, the economy, the labor market and to substantially reduce energy consumption. One of their main objectives is working to ensure green certified materials and products would be readily available in the Kuwaiti market. They are still a relatively new council and are working hard to make changes. They are currently working on making green cleaning products available in the local market. Their vision is to encourage and engage both public and private sectors to adopt sustainable measures in the development sector in Kuwait. Hopefully they will be able to accomplish their goal and LEED will be easier to achieve in the near future in Kuwait.

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Building Energy Performance Analysis of an Academic Building Using IFC BIM-Based Methodology

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Abstract:
This paper discusses the potential to use an Industry Foundation Classes (IFC)/Building Information Modelling (BIM) based method to undertake Building Energy Performance analysis of an academic building. BIM/IFC based methodology provides a mechanism for providing quick and cost-effective feedback to building users. The paper discusses the need for IFC and BIM-based analysis of existing buildings. A case study of Building Energy Performance Analysis of an academic building is presented with a detailed discussion on various interventions undertaken to calibrate the model. The paper concludes that BIM/IFC based approaches provide a feasible alternative to conduct energy analysis of existing buildings provided various correlations are built into the model.

Keywords:
Building Information Modeling, Building Energy Performance Analysis

1. Introduction

Building operations consume massive amount of energy and account for 40% of global Green House Gas (GHG) emissions (UNEP, 2006). As result of increasing awareness of environment impact of buildings and rising prices of fossil fuels, the need for enhancing building performance through energy consumption reduction is increasingly being realised. Reducing the energy consumption in our residential and commercial buildings will have a huge impact on UK's total energy savings.

Existing approaches for building energy performance (BEP) analysis are either prohibitively expensive (e.g. detailed energy audits by BREAM certified experts) or inadequately granular and not providing enough energy feedback (e.g. carbon calculators, energy benchmarks, ROI curves). This is also constrained by limited availability of building energy performance experts. Also, traditional approaches to BEP analysis incur huge time delays in energy model preparation before useful information is made available to support building operations or retrofit decisions. Huge costs, complexity and time delays incurred in producing BEP results mean that it is not commonly used in building operations. Thus, there is need to complement high budget and time consuming traditional BEP analysis approaches with low-cost innovative methods to meet carbon reduction goals.

IFC/BIM Based methodologies for Building Energy Performance (BEP) simulation provide a mechanism for quick feedback to users. Also, use of IFC/BIM based BEP methods are driven by UK government agenda to make usage of BIM mandatory (UK Government Construction Strategy, 2011). Usage of BIM based BEP simplifies the process by using existing Building Information Models, where available. Thus, IFC/BIM approaches have a significant potential to reduce simulation time and improve model accuracy.

This paper presents a case study of BEP analysis of an academic building using IFC BIM-Based Methodology. Initially the need for IFC and BIM-based analysis of existing buildings is discussed. This is followed by discussion of a case study that discusses the energy analysis process in detail and various interventions undertaken to calibrate the model. Final Section discusses various technical and cost challenges associated with energy consumption feedback and using such analysis to support retrofit decision making.

1. Case Study Description

For the case study, an academic building at University of Salford campus was chosen (Figure 1). There is a tremendous interest within University of Salford in the area of sustainability and energy efficiency improvements. University has also launched Carbon Management Plan with an aim to reduce Carbon emissions by 30% in comparison with 2005/2006 levels over a 5 years period. A BIM model of Maxwell building was produced (Figure 2), representing accurate building mass and envelope. Accurate representation of building materials such as insulation used for building envelope is essential for correct calculation of heat losses. Energy analysis software (Autodesk, 2013) were utilised to undertake preliminary environmental performance assessment. The software uses building mass to predict energy intensity (kWh/ square footage) of a particular building. Data from nearest weather station was used to collect climatic data such as highest and lowest temperatures over the year, amount of rainfall on average for the region, wind forces, solar radiation etc. Such climatic information serves two pronged objective. Firstly, it helps achieve accurate calculations for energy use prediction. Secondly, it helps in computation of potential renewable energy gains resulting in more sustainable and efficient building. Building data related to operating schedule, details of HVAC system and actual electricity and fuel consumption data was obtained from estates department at University of Salford. Results from energy simulation such as electricity/ fuel consumption rates, carbon emissions, life cycle energy use/ cost etc were benchmarked against actual consumption rates obtained from the building operations team.

The first iteration showed a wide variance of results between the actual building energy consumption data and results obtained from BIM based energy simulation analysis. From the numbers provided by the Estates Department at Salford University, the annual electricity consumption for the case study Building was estimated to be approximately 3,690,116 kWh, while annual gas consumption is estimated as 3,622,900kWh. However, the results from energy simulation analysis indicated an annual consumption of 5,360,000 kWh, an over-estimation by 1,650,000 kwh. It was important to calibrate the energy simulation results leading to this accuracy.

Figure 1: Case Study Building

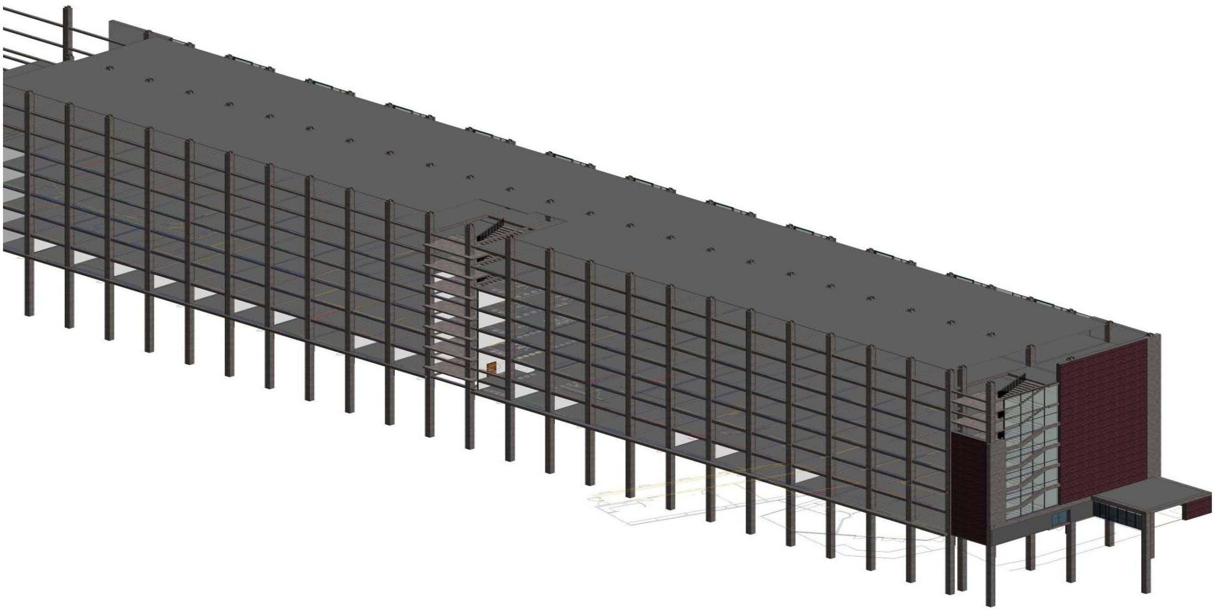

Figure 2: Sectional view of the Case Study Building 3D Information Model

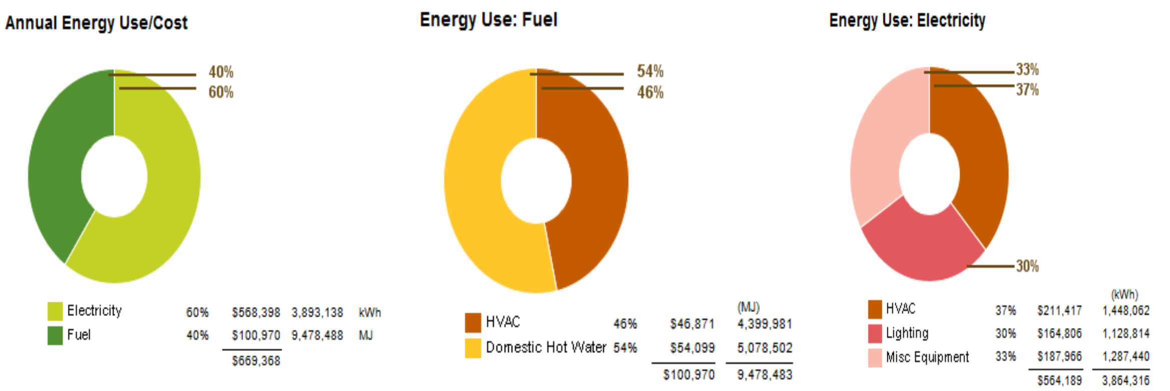

Figure 3: Energy Consumption Results

In order to correct the inaccuracy, various energy settings available within the software were investigated. Revit Architecture provides the user with a choice of of different HVAC systems. Each system would impact differently on the energy consumption rates. A list of all possible choices was explored working with building operations team. The HVAC system used in the building is of type 12 SEER/0.9 AFUE Split/Packaged Gas, 5-11 Ton. There is no HVAC option available in the energy analysis tool that actually matched installed HVAC system in the building. However, the option that closely matched the system that is installed was chosen. This substantially reduced the variance between the estimated and actual energy consumption results.

Software results were further calibrated through accurate input of building operating schedule. Initial energy calculations used the assumption that building operates throughout the year on a 24/7 routine, with an exception of couple of day's closure during Christmas holidays. Thus, an operating schedule of 24/7 building usage for 363 days was used for initial energy simulation results. However, discussions with estates staff at University of Salford showed that building opening hours do not correspond with actual energy consumption, which is much lower during weekend and night hours, when most of the building occupants have left. Thus, amount of energy (electric, light, electric equipments) consumed at night time is lower than that used in morning hours. Even during winters, the heating is not switched on 24/7, rather operates in a 19/7 cycle for 6 months of the year. Based on discussions with building operations team, building operating routine was set equivalent to a facility operating 12 hours per day and 7 days a week. This resulted in further improvements in results accuracy, by lowering down the building energy consumption estimate to 4,106,000 kWh, in comparison with actual energy consumption data of 3,690,000 kWh, as provided by the Estates Department.

The case study building was constructed over 50 years ago and few corrections were made to correct target glazing percentage inside the building. It is important to use correct glazing levels of the building as most of the heat is lost through openings such as windows. BIM model of the building, alongside actual digital photographs were used to accurately calculate the glazing percentage for the larger façade of the building, which was calculated to be approximately 55%. Since the glazing does not take up the same percentage from every wall, some additional calculations were made to determine that the glazing percentage of the entire building façade is approximately 51 %. Changes in the glazing percentage resulted in energy consumption estimates of 3,864,000 kWh. This meant that the energy intensity (kWh/square foot) results as predicted by BIM based energy analysis software were within 5 percent of the actual energy consumption data.

2. Discussion and Conclusions

The research has demonstrated that BIM/IFC based approaches provide a feasible alternative to conduct energy analysis of existing buildings, provided various correlations are built into the model. The approach does not require specialist energy assessor, auditor or a software expert. After initial calibration, results were obtained within a 5% margin of accuracy. The results could be used for preliminary energy analysis and for exploring various alternatives to enhance building performance using renewable energy.

One of the key limitations of conventional methods and schemes for environmental performance assessment of buildings is that they do not adequately take into account actual building operations data. Thus, there are many cases where buildings rated BREEAM Excellent or having outstanding performance actually use more energy than the old buildings they have replaced. Some of the promising features of BIM-based energy performance analysis is that it helps predict key data related to building energy consumption. Also, the approach is visually appealing with graphs and images providing an engaging mechanism to provide feedback to building users on building energy consumption reduction and carbon-neutrality potential and for quick comparisons to be made with actual energy consumption data. There is a potential of deployment of such approaches on projects where quick input on various energy related retrofit decisions are required.

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