Building Simulation 2009

Eleventh International IBPSA Conference
Glasgow, Scotland
July 27-30, 2009

KEY FACTORS - METHODOLOGY FOR ENHANCEMENT AND SUPPORT OF BUILDING ENERGY PERFORMANCE

Andrea Costa[1,2], Marcus Keane[1], Paul Raftery[1,2] James O'Donnell[1]
[1]National University of Ireland, Galway, Ireland
[2]Lawrence Berkeley National Laboratory, Berkeley, California, USA
Corresponding author: a.costa1@nuigalway.ie

ABSTRACT

This paper presents the Key Factors methodology that supports energy managers in determining the optimal building operation strategy in relation to both energy consumption and thermal comfort. The methodology is supported by the utilisation of calibrated building energy simulation models that match measured data gathered by an extensive measurement framework. The paper outlines the proposed methodology defining the underpinning concepts and illustrating the performance metrics required to capture the effect of different building operation strategies. A brief case study is discussed to demonstrate the application of the methodology.

INTRODUCTION

Prescriptive based approaches to the design, construction and operation of buildings have substantially failed to deliver operationally energy efficient buildings (Koskela 2000). Performance based assessment is now being promoted and several performance rating methodologies have been developed worldwide (Morrissey 2006).

Focusing on building operation, energy efficiency measures can be effective in addressing the problem of high building energy consumption. In particular, considering the existing building stock, there is large scope for energy savings. In relation to that, Continuous Commissioning (CC^{SM}) is an approach that was first established in USA that has achieved an average reduction of over 20% of the total energy cost in more than eighty American buildings (D.E. Claridge et al. 1996). Continuous commisioning denotes an ongoing process for the quality assurance of building performance. It is a process designed to develop targets in terms of energy effiecency and to verify and document their achievement. CC is seen as a prerequisite for the long term energy efficient operation of buildings (Jagemar & Olsson 2007).

Accordind to (Liu et al. 2003) the starting point of this process is typically an energy audit during which CC measures are identified. This is then followed by a second phase during which the CC measures are refined and implemented following six steps: 1) develop the CC plan and form the project team, 2) develop performance baselines, 3) conduct system measurements and refine proposed CC measures, 4) implement CC measures, 5) document comfort improvements and energy savings, and 6) keep the commissioning continuous (D. E. Claridge et al. 2003).

However, while researchers have demonstrated success by bringing in CC experts who use their knowledge, experience and resources to 'fix' building systems (Baumann 2005) few tools are available to the on-site engineer or energy manager to conduct such improvements (O'Donnell 2009) (Piette et al. 2001). In relation to this, the goal of Annex 47 (IEA 2005) is to develop commissioning techniques, tools and methodologies that will help transition of the industry from the intuitive approach that is currently employed in the operation of buildings to a more systematic approach that focuses on achieving significant energy savings. Thus this paper proposes a new performance based methodology, named "Key Factors methodology" that intends to support the energy manager in easily determining the most effective operation strategy in terms of comfort provided and building energy consumption.

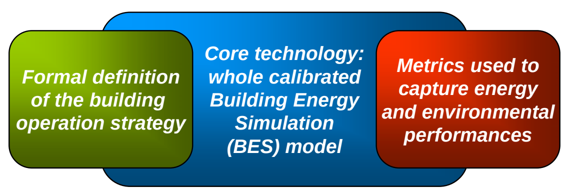


Figure 1 - Key Factors methodology - requirements overview

Figure 1 shows the requirements of this methodology that will be explained in detail in the subsequent sections of this paper. To achieve the expected results it is essential to define performance metrics to assess energy and environmental building performances and also a rigorous way to formally represent a specific building operation strategy that can be tested and compared against others. The core technology adopted in this methodology is a calibrated whole Building Energy Simulation (BES) model capable of capturing environmental and energy performances according to the predefined metrics. The BES model calibration process is defined within an ongoing and separate research work (Raftery et al. in press).

CALIBRATED BES MODELS

Dynamic Building Energy Simulation (BES) models are a mean of reducing greenhouse gas emissions and can provide substantial improvements in fuel consumption (Hensen et al. 2004). However, BES models are primarily used at the design stage of the Building Life Cycle (BLC) (Maile et al. 2007) and not at the operation stage. This is because when assuming values and schedules for most of the input parameters the results are meaningful only for a comparison analysis between different design choices and are not accurate enough to predict the energy consumption during operation. Assuming that an adequate measurement framework is in place and a calibrated BES is available, these models can be used to investigate and optimise energy performance during the operation stage of the Building Life Cycle (BLC).

This demands an extensive physical measurement framework capable of gathering data to be used as building specific input for BES models. This need has driven both industry and academia to develop more robust and reliable cost effective measurement technologies to obtain values not only at the building level but also at more detailed level such as system components and thermal zones (BuildWise 2007). The resulting instrumented measurement framework gives the opportunity to measure different parameters from real buildings and use these measured values in place of those normally assumed with a significant margin of error during the design phase (W. L. Lee et al. 2001). For example, with a set of electricity meters, it is possible to measure the real lighting and plug loads and their effective schedules for each zone, likewise for system components such as a fan or a pump. With CO_2 level or PIR sensors it is be possible to identify proper occupancy patterns within a given zone, etc. These measurements are also beneficial for fault detection activities (Building EQ 2009).

Therefore, a proper measurement framework can obtain building specific information for many of the parameters that are needed to input into the model and mitigates the number of assumptions that need to be made. Consequently BES models can be calibrated in order to provide outputs that match measured energy consumption.

As this is a difficult task, it requires a formal calibration process that is currently under development under separate research and has already been published in part (Raftery et al. in press).

There are at least **three downstream advantages** arising from the use of calibrated energy simulation models during the operation stage of the BLC.

1. *Continuity and consistent predictions* - The first important advantage is that, thanks to the available data streams and energy simulation models, it will be possible to **explicitly tie the design intent to the energy performance of the real building**. With a model-based assessment it will be possible to measure the same metrics during both design and operation and compare predicted to measured performance. This will in turn improve the design quality of new buildings as they will be more performance oriented (O'Donnell 2009).
2. *Support energy managers* – A calibrated energy simulation model represents **a live, ideal building specific energy benchmark for a given building during its operation**. This will be a significant advantage for energy managers in monitoring the energy consumption of their buildings.
3. *Enhancement of the operation* strategy - The third advantage will be to facilitate the testing of different operation strategies in the model virtual environment **analysing the influence of each change in operation strategy on both the energy consumption and the occupant comfort.** In this manner, a more accurate selection of the most efficient operation strategy for a given level of comfort is possible. This process is formally described by the Key Factors methodology presented in this paper.

KEY FACTORS METHODOLOGY

Underpinning concepts

The objective of the Key Factors (K_f) methodology is to support energy managers in determining the optimal building operation strategy in relation to both energy consumption and occupants comfort. The Key Factors (K_f) are those parameters of the operation strategy that influence the environmental and energy performance of the building. Examples include temperature set-point, lighting levels set-point etc… The determination of the optimal building operation is done following a systematic procedure. It consists of defining a process that allows evaluation of energy performance and thermal comfort resulting from changes to values and schedules that relate to the building's Key Factors. The effects of these changes are investigated in the virtual environment of the calibrated building energy simulation model and conveyed to the user in a structured and effective way.

The final goal is to reduce building energy consumption in a cost effective way. For this reason, this methodology focuses on the optimisation of the operation strategy, which requires only changes in the control parameters; this is much more convenient than other improvements or Energy Conservation Measures (ECM) such as improvements to building envelope or system and plant retrofits.

Other researchers have done similar work regarding optimisation of building operation and control. Burhenne (Burhenne & Jacob 2008) focuses on the optimisation of the pump schedule of the heating circuit. In this case, the set-point temperature in the conditioned space is given as a boundary condition with the aim of optimising system component operation. In our case, the set-point temperature will be investigated as a variable instead of being a boundary condition. The idea is to carry out a model-based choice of the operation strategy of the building in relation to predefined metrics. This means, for example, that the set-point temperature in the conditioned space will be occupancy and comfort driven instead of a default values and schedules as common practice.

Nowadays building performance control is done normally on a monthly basis by evaluating energy consumption, which is based on utility bills, and by monitoring the occupant comfort, which is based on received complaints. Within this timescale, any effect of a single change in building operation is evaluated over a period of one month (and in some cases one year) comparing the result of the energy consumption with the previous years and taking into account the influence of a different external climate. This is usually done with weather normalization (typically using the degree-days method). Calibrated building energy simulation models offer a virtual environment in which to test potentially thousands of different modifications to operation strategies and quickly evaluate their effects on the monthly/yearly energy consumption and occupant comfort.

The Key Factors (K_f) methodology proposes to focus on the relationship between energy consumption, thermal comfort and the operation strategy defined by the Key Factors set (K_f SET). The set contains a specific schedules and values combination of the selected Key Factors.

The Key Factors are dependent on the available actuators in the considered building and on its HVAC system components. The larger the number of actuators, the more control the user has over the operation strategy. Ideally, every single parameter that controls an actuator can be considered a Key Factor. In practice though, future studies will focus on a Sensitivity Analysis to identify which are the most effective Key factors in terms of coupled energy consumption and thermal comfort.

From an application perspective, the two important assumptions on which this methodology stands include:

1. Building Energy Simulation models can be systematically calibrated and can produce results which closely match real building operation;

The level of resolution to which the calibration will focus on is the highest possible in relation to the available measured data, as outlined by (Raftery et al.in press). This is not the main focus of this work as the calibrated BES models represent the starting point of the Key Factors methodology.

2. Meters, sensors and actuators are available at a low cost and are extensively adopted in the building considered.

The main barrier to defining and deploying an adequate number of sensors and meters in a building is the cost required for the installation, which is mainly due to the wiring. In fact, over the total cost for a new sensor, the incidence of the wiring cost is 45% and 70% respectively for a new building a retrofit application (Jang et al. 2008). In response to this need, both industry and academia have been achieving results in developing and deploying wireless sensor technology to the construction sector. Several studies have been carried out regarding the possibility to extend this wireless technology to sensors, meters and actuators and some results have been achieved (BuildWise 2007).

Implementation level

From an application perspective, we need firstly to identify the user profiles and their tasks in this process. As shown in Figure 2 an external energy consultant will provide a calibrated Building Energy Simulation (BES) model and the energy manager will specify the metrics that the model will have to output to check the effects of the changes in the operation strategy he would like to test. At this stage of the work, the choice of the metrics focuses on building energy consumption and user thermal comfort.

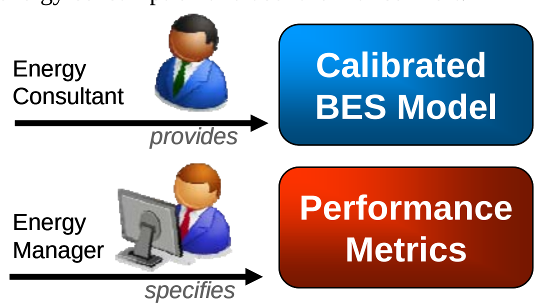


Figure 2 Users Profiles and Tasks Definition

In future, the number of performance metrics could be increased to consider other aspects such as building energy related CO_2 footprint. However, a limited number of metrics is by far the best way to compare the effects of different operations strategies.

Assuming that a calibrated building energy simulation model is available and ready to output the performance metric as specified, it is handed over to the energy manager, who will run the first simulation with the Baseline Key Factors set (K_f SET). This consists of a set of all the control parameters that are used in the current operation strategy of the building and represent the baseline case. This is the starting point at which future improvements are compared. As the BES model is calibrated, the output results will match the measured energy consumption and the overall thermal comfort of the occupants, which is generally informally measured on the basis of the complaints received or spot surveys. After running the first simulation with the Baseline K_f set the baseline values for the identified metrics are stored in a Performance Table (Figure 5).

At this point, the energy manager begins the testing activity (Figure 3) exploring other possible operation strategies and checking their impact on the energy consumption and the thermal comfort within the virtual environment of the calibrated Building Energy Simulation model. The energy manager defines a new Key Factors set for any different operation strategy he wants to implement. He then runs the model and stores the results in the Performance Table (Figure 5).

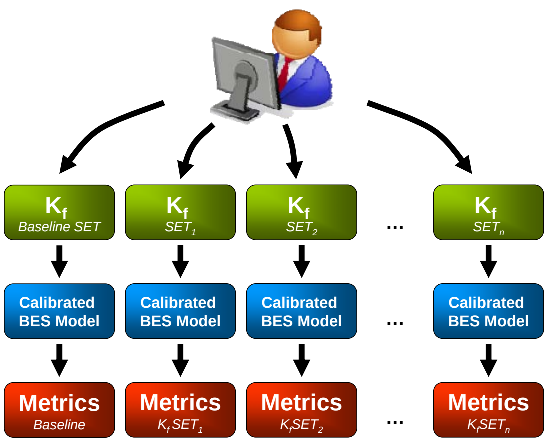


Figure 3 Testing of different Key Factors sets

The values of the Key Factors, that define a K_f SET, can vary according to the time or to the external conditions. The latter would be the case of an adaptive comfort operation strategy (Brager & de Dear 2001). The values and the schedules can also vary in relation to the different zone types within the building (Figure 4).

Performance Metrics definition

As stated in the previous paragraph, the choice of the metrics focuses on two main macro aspects of building performance: energy consumption and user thermal comfort.

Energy Usage Intensity (EUI) is selected as the energy consumption metric. This represents the total annual amount of primary energy supplied to the building weighed over the net conditioned area. This takes into account both the ideal building energy demand for given boundary conditions and the system efficiency. Consider the useful energy, which is intended as the energy needed to maintain given comfort conditions in the space with an ideal HVAC system, is a possible alternative option. However, this option is not ideal because it does not take into account that different operation strategies have different effect on the real system efficiency. The Operational Building Energy Rating (BER) certificate class (Jagemar & Olsson 2007), once it is calculated, can be shown in conjunction with the respective EUI value (Figure 5).

	PERFORMANCE METRICS					
OPERATION STRATEGY	EUI [kWh/m²y]	BER [Class]	D_{AV} [%]	$DF_{10\%}$ [%]	$DF_{15\%}$ [%]	$DF_{20\%}$ [%]
K_f Baseline SET	$X_{Baseline}$	$Y_{Baseline}$	$Z_{Baseline}$	$K_{Baseline}$	$W_{Baseline}$	$J_{Baseline}$
K_f SET_1	X_1	Y_1	Z_1	K_1	W_1	J_1
K_f SET_2	X_2	Y_2	Z_2	K_2	W_2	J_2
...	...	...	...	...	...	...
K_f SET_n	X_n	Y_n	Z_n	K_n	W_n	J_n

Figure 5 Performance Table

The occupant thermal comfort metric is expressed by (1) and it is based on the Predicted Percentage of Dissatisfied (PPD). The weaknesses of this mathematical model have been documented, especially in relation to adaptive comfort (CIBSE 1999). However, we need a metric able to numerically represent thermal comfort and this is currently the only formally accepted criteria defined in the standards (ASHRAE 2004).

$$D_{AV} = \frac{\sum_{i=1}^{z} \sum_{k=1}^{n} PPD_{i,k} \cdot O_{i,k} \cdot Zt_i}{z \cdot n} \qquad \textbf{(1)}$$

As shown in (1) D_{AV} is the value of the dissatisfied people averaged annually over occupancy and different zone types.

n – is the number of time intervals in a year;

z – is the number of zones in the building;

$PPD_{i,k}$ – is the PPD value at the time step k in the zone i;

$O_{i,k}$ – is the occupancy factor at the time step k in the zone i that takes into account a varying occupancy profile throughout the year. It is expressed as a percentage of the maximum occupancy value;

Zt_i – is the Zone type (Zt) dependent factor that

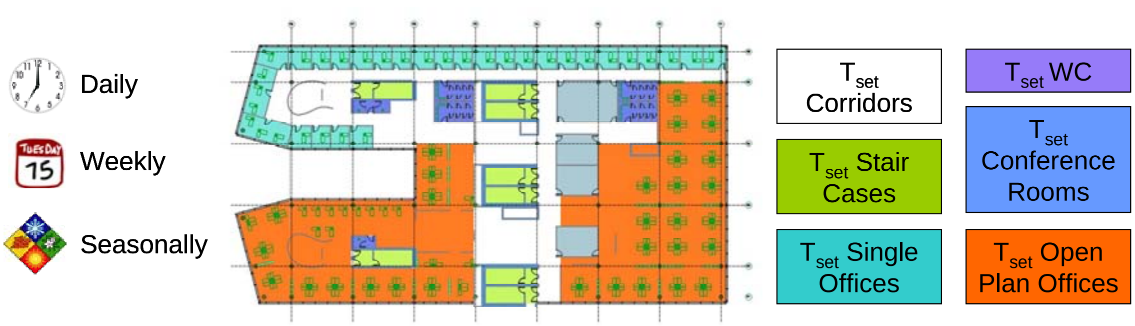


Figure 4 Key Factors variation according to time or zone type

associates a level of priority of the thermal comfort required in the zone *i*. It is expressed as a percentage of the maximum value. For example, in an office building, a low PPD for a hallway or a stair case zone should have less of an impact than the same parameter in an office zone. Higher values are used in zones where people spend most of their time and are performing their work.

Minimum occupancy will still demand minimum comfort and the average value is not sufficient to understand the level of comfort provided by a certain operation strategy. For this reason, the discomfort frequency parameters (DF_r) are introduced (2).

$$DF_r = \frac{\sum_{i=1}^{z}\sum_{k=1}^{n}\left[PPD_{i.k}\right]^{>r}}{z\cdot n} \qquad \textbf{(2)}$$

They represent the percentage of hours during which the instantaneous value ($PPD_{i,k}$) is out of the range *r* and the zone *i* is occupied. This is equal to the thermal comfort Performance Indicator number three (PI3) proposed by Augenbroe that refers to 10% range of dissatisfied (Augenbroe & Park 2005). In our case, three ranges are considered: 10%, 15% and 20%.

Once the Performance table (Figure 5) is populated with all the values of the metrics described for each Key Factors set, it is possible to display the results in a graphical fashion (Figure 6).

CASE STUDY

A brief case study was performed to show how this methodology can be applied in practice. The example is an office building located in Ireland (Figure 7).

It is four stories high with a total gross area of approximately 30,000 m^2. In the ground floor, there are different types of zones such as a kitchen, a canteen and other facilities areas. On the other three floors, the space is divided between open offices, conference rooms and service areas.

Energy Plus was chosen as the simulation engine for the BES model. The model used has not yet been calibrated to measured data because the required measured framework is not in place. Therefore, this case study is a *demonstration* of how the methodology will work for a building with a calibrated BES model.

In order to reduce the level of complexity only one Key Factor will be examined in this demonstration: the indoor set-point temperature.

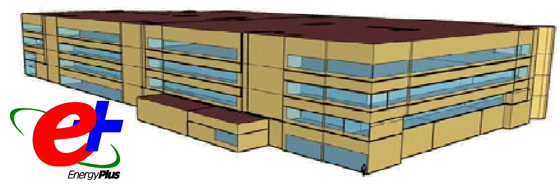
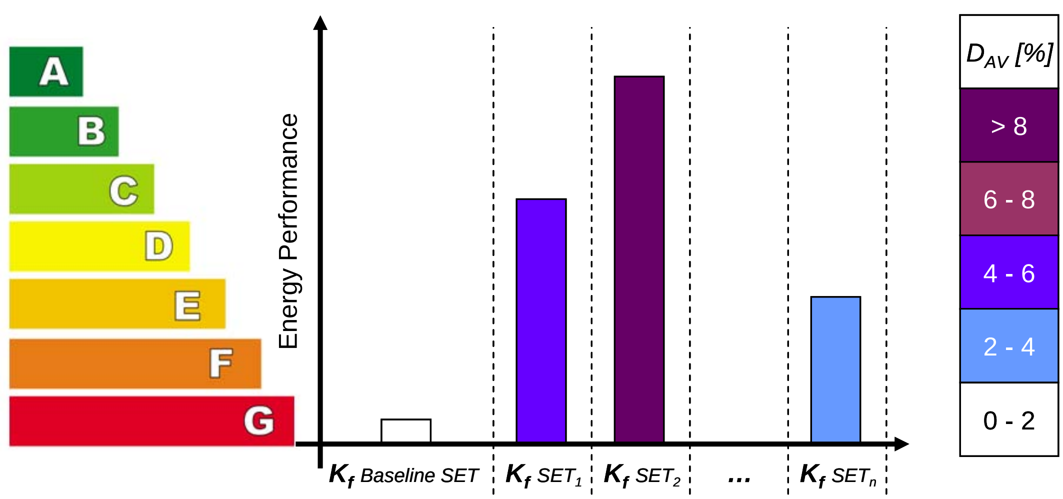


Figure 7 BES model for example building

The building is operated 24 hours a day and maintained within a 20°C to 22°C temperature range. This represents the K_f Baseline set. Four other Key factors sets, which are obtained by changing the temperature range, are tested:

- K_f SET$_1$ – 20°C to 24°C temperature range
- K_f SET$_2$ – 19°C to 23°C temperature range
- K_f SET$_3$ – 18°C to 22°C temperature range
- K_f SET$_4$ – 19°C to 22°C temperature range

Figure 8 shows the performance table with the results of these different Key Factor sets. For the calculation of D_{AV} the zone type parameter (Zt_i) was kept



$X_{Baseline}$	X_1	X_2	…	X_n	*$DF_{10\%}$ [%]*
$Y_{Baseline}$	Y_1	Y_2	…	Y_n	*$DF_{15\%}$ [%]*
$Z_{Baseline}$	Z_1	Z_2	…	Z_n	*$DF_{20\%}$ [%]*

Figure 6 Key Factors variation according to time or zone type

constant and equal to 1. Every zone in the building in this brief demonstration case has been considered with the same level of priority.

The Operational BER value is not available since a formal operational assessment procedure is still missing in Ireland and in many other EU member states.

As expected, a significant decrease in energy consumption is achieved by increasing the cooling set-point. Moving from a maximum of 22°C to 23°C the reduction of the EUI is equal to 31 kWh/m^2 yearly. With a cooling set-point of 24°C the energy saving is even larger (66 kWh/m^2). However, it is important to notice how the level of thermal comfort provided decreases accordingly. For example the PPD is grater than 10% for the 77.3% of the time when using a cooling set-point of 24°C (SET_1)

The reduction of the heating set-point temperature, tested with the third and fourth set of Key Factors does not significantly affect energy consumption. This is expected because the combination of the mild Irish weather and high internal loads (lighting and equipment) ensures that the building requires cooling almost constantly to maintain the temperature within the required range. However the operation strategy implemented with K_f SET_4 provide the same level of comfort and slightly lower energy consumption (0.2%) than the baseline case. Although this improvement is small when compared to the level of accuracy of the model, this result shows how it is possible in theory to save energy using this methodology. More savings are expected by changing the schedules to match the actual building specific occupancy patterns for the different zone types. The majority of these cases result in a trade off between thermal comfort and energy performance and thus are not acceptable changes to operation strategy. However, it should be noted that this study is based on an initial model that has not been calibrated and also that only one parameter was considered.

	PERFORMANCE METRICS					
OPERATION STRATEGY	EUI [kWh/m^2y]	BER [Class]	D_{AV} [%]	$DF_{10\%}$ [%]	$DF_{15\%}$ [%]	$DF_{20\%}$ [%]
K_f Baseline SET	584	n/a	3.48	38.3	4.6	0.4
K_f SET_1	518	n/a	6.12	77.3	54.7	27.0
K_f SET_2	553	n/a	4.63	64.5	26.4	5.1
K_f SET_3	583	n/a	3.47	38.7	4.6	0.4
K_f SET_4	583	n/a	3.47	38.3	4.6	0.4

Figure 8 Case study results

High levels of dissatisfaction obtained for the baseline operation strategy require a more detailed study of the BES that will be undertaken during the calibration process. Other comfort prediction models such as Pierce or KSU (US-DOE 2005) will be also investigated as part of future work.

CONCLUSION

The proposed Key Factors methodology supports energy managers in determining the optimal building operation strategy in relation to both energy consumption and thermal comfort. This is achieved using a calibrated BES model during the operation stage of the BLC. An adequate building measurement framework is required and a systematic calibration process has to be performed to support the methodology. The case study shows how different operation strategies can be tested in the model and the results can be compared in order to predict the effects of real changes in operation. This new model-based decision making will enhance the effectiveness of energy managers in monitoring and improving energy consumption of their buildings.

FUTURE WORK

The process that has been described is a manual process in which the energy manager selects and tests different Key Factors sets in an attempt to optimise the building operation strategy.

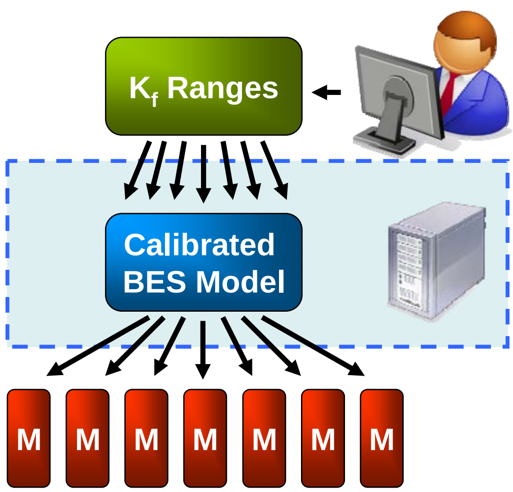


Figure 9 Automated process from Key Factors sets to Performance Metrics

The next step will be to set up several ranges (Figure 9) for the selected Key Factors. The BES model will be run in batch mode testing the different possible combinations and automatically populating the Performance Table (Figure 5). In turn, this process would automatically select the optimal operation strategy that corresponds to the Key Factors set with the least energy consumption for a required level of thermal comfort. Wright (Wright et al. 2002) proposes to apply multi-objective genetic algorithm (MOGA) in the identification of the optimum pay-off characteristic between the energy cost of a building and the occupant thermal discomfort. A similar approach can be used for this automation process. The use of the generic optimisation program GenOpt (Wetter 2004) will be considered for the methodology application in the future work.

The research plan is intended to extend this optimisation to a real time basis. The data streams gathered by the measurement framework will be used for live pattern recognition and fault detection. The measured data will be compared to the output of a model based on the simple hourly method (ISO 13790 2008). This method requires less computation capacity than a detailed simulation as was used for this methodology and this is better for a real time application.

From an application perspective, the methodology will be applied using a calibrated BES for the test case building. In addition, the aforementioned Pierce and KSU thermal comfort models will be investigated.

ACKNOWLEDGEMENT

This paper was made possible by funding from Enterprise Ireland within the BuildWise research project.

REFERENCES

ASHRAE, 2004. *Standard 55-2004 – Thermal Environmental Conditions for Human Occupancy*, American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc.

Augenbroe, G. & Park, C., 2005. Quantification Methods of Technical Building Performance. *Building Research & Information*, 33 (2), 159-172.

Baumann, O., 2005. Enhanced Building Operation Using `Operation Diagnostics' -A Case Study. In *International Conference for Enhanced Building Operations, October 11-13,2005 Pittsburgh, PA, USA*.

Brager, G.S. & de Dear, R., 2001. A new adaptive comfort standard for ASHRAE Standard 55.

Building EQ, 2009. Building EQ - intelligize your energy management: homepage:: Available at: http://www.buildingeq-online.net/ [Accessed February 14, 2009].

BuildWise, 2007. BuildWise. Available at: http://zuse.ucc.ie/buildwise/.

Burhenne, S. & Jacob, D., 2008. Simulation Models To Optimize The Energy Consumption Of Buildings.

CIBSE, 1999. *Environmental Design CIBSE Guide A*, Yale Press Ltd.

Claridge, D.E. et al., 2003. *Manual of Procedures for Calibrating Simulations of Building Systems*, California Energy Commission.

Claridge, D. et al., 1996. Can You Achieve 150 Percent Predicted Retrofit Savings: Is It Time for Recommissioning? In Washington D.C., USA: American Council for an Energy Efficient Economy, pp. 73-88.

Hensen, J. et al., 2004. BUILDING PERFORMANCE SIMULATION FOR BETTER DESIGN: SOME ISSUES AND SOLUTIONS.

IEA, 2005. *Annex 47: Cost-Effective Commissioning for Existing and Low Energy Buildings*, International Energy Agency.

ISO 13790, 2008. ISO 13790 - Energy performance of buildings - Calculation of energy use for space heating and cooling.

Jagemar, L. & Olsson, D., 2007. The EPBD and Continuous Commissioning.

Jang, W., Healy, W.M. & Skibniewski, M.J., 2008. Wireless sensor networks as part of a web-based building environmental monitoring system. *Automation in Construction*, 17 (6), 729-736.

Koskela, L., 2000. *An Exploration towards a Production Theory and its Application to Construction*. Text.Thesis.Doctoral. Available at: http://lib.tkk.fi/Diss/2000/isbn951385566X/ [Accessed March 3, 2009].

Lee, W.L. et al., 2001. Energy saving by realistic design data for commercial buildings in Hong Kong. *Applied Energy*, 70(1), 59-75.

Liu, M., Claridge, D. & Turner, W.D., 2003. Continuous Commissioning of Building Energy System. *Journal of Solar Energy Engineering*.

Maile, T., Fischer, M. & Bazjanac, V., 2007. Building Energy Performance Simulation Tools - a Life-Cycle and Interoperable Perspective. *CIFE Working Paper WP107*, STANFORD UNIVERSITY, 49.

Morrissey, E., 2006. *Building Effectiveness Communication Ratios (BECs): An Integrated 'Life-Cycle' Methodology for Mitigating Energy-use in Buildings*. PhD Thesis. University College Cork.

O'Donnell, J., 2009. *Specification and Communication of Building Performance Information for Holistic Environmental and Energy Management*. University College Cork.

Piette, M.A., Kinney, S.K. & Haves, P., 2001. Analysis of an information monitoring and diagnostic system to improve building operations. *Energy and Buildings*, 33 (8), 783-791.

Raftery, P., Keane, M. & Costa, A., Calibration Of A Detailed Simulation Model To Energy Monitoring System Data: A Methodology And Case Study.

US-DOE, 2005. *EnergyPlus Energy Simulation Software*, U.S. Department of Energy. http://www.eere.energy.gov/buildings/energyplus/. Available at: http://www.eere.energy.gov/buildings/energyplus/.

Wetter, M., 2004. GenOpt, generic optimization program, user manual,version 2.0.0. Technical report LBNL-54199, Lawrence Berkeley National Laboratory.

Wright, J.A., Loosemore, H.A. & Farmani, R., 2002. Optimization of building thermal design and control by multi-criterion genetic algorithm.