BUILDING EFFECTIVENESS COMMUNICATION RATIOS FOR IMPROVED BUILDING LIFE CYCLE MANAGEMENT

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ABSTRACT

Many existing building energy performance assessment frameworks, quantifying and categorising buildings post occupancy, offer limited feedback on design decisions. An environment providing decision makers with pertinent information to assess the consequences of each design decision in a timely, cost effective and practical manner is required to promote viable low-energy solutions from the outset. This paper outlines a performance-based strategy utilising building effectiveness communication ratios stored in Building Information Models (BIM). Decision makers will be capable of rating the building's energy performance throughout its natural life cycle without imposing adverse penalties on facilities located in dissimilar climatic zones subjected to stringent building codes and regulations. With this advancement in building energy assessment in place, a progressive improvement in energy efficiency for the building stock is a feasible and realistic target.

INTRODUCTION

According to recent publications from the American Institute of Architects Committee, construction and operation of buildings consume 35% of total US energy production. It is also estimated that buildings consume more than 60% of the electricity generated in the US and this energy accounts for at least 35% of the total amount of US CO_2 emissions. In Europe, current figures reveal 40% of energy production being consumed by buildings, which amounts to 30% of total CO_2 emissions. In order to address this increasingly critical concern, the European Parliament implemented Energy Performance in Buildings Directive (EPBD) 2002/91/EC in January of 2003. This building energy directive places demands on facility owners to quantify the energy usage of their buildings against benchmarks set by government agencies throughout the building life cycle by January 2006. The directive, whilst differentiating between new and old buildings, subjects both sets of buildings to enhancement of building energy performance. Clients of new facilities are presented with energy certificates which act as benchmarks for the building's energy performance appraisal. It is envisaged that this directive will coerce clients to insist on more energy conscious buildings and place a responsibility on the AEC&FM community to design, construct and operate these buildings with improved envelopes and HVAC strategies in association with quantifiable energy ratings across the entire building life cycle.

With virtually every decision made over the life cycle of a building having long and short term energy-performance consequences, a clear *feedback loop structure* associated with building design would facilitate a client's assessment of decisions made by the design team in order to obtain a 'minimum energy use' building. Many approaches have been sought in order to address the issue of quantifying and categorising buildings for building appraisal purposes, including ICC (ICC 2000) in the US and BREEAM (BREEAM 2005) in the UK. However, these frameworks offer an overall indicator of the building's *environmental* performance and do not present any feedback loop to the design stage. Additionally, these environmental evaluations occurs downstream of the building life cycle, subsequent to all design decisions, with little categorisation of utilised management strategies and HVAC design related to minimum energy use for the building. This important weakness in assessment, tied with the intrinsic difficulty in relating any ratings to these design decisions, delivers little building energy-use evaluation.

Undertaking building energy simulation at the earliest design stage offers a means to significantly increase performance throughout the building life cycle. However energy simulation modelling has not been widely adopted by the design community. This is due, in part, to the fragmented nature of the building industry and also due to the complexity of the simulation tools. The time required preparing input information and process the output is an objectionable project overhead. Even experienced users in simulation modelling require significant time in preparing objective energy models. An additional barrier is the lack of energy appraisal tools capable of modelling a wide spectrum of hybrid HVAC systems combined with low market interest and the high time-cost of energy performance prediction. Code compliance during design stages is as far as most building designers go with respect to considering building energy performance (Papamichael 2002). Consequently, building energy related performance criteria are still considered only in a small fraction of building designs and retrofits and, in most cases, after completion of design. This results in only marginal performance improvements (Figure 1). These ‘improvements’ often take the form of “out of the box” technologies for specific building component and systems. Proficient utilisation of energy simulation and energy performance assessment within the design community is necessary to promote an improvement in the energy performance of the entire building stock.

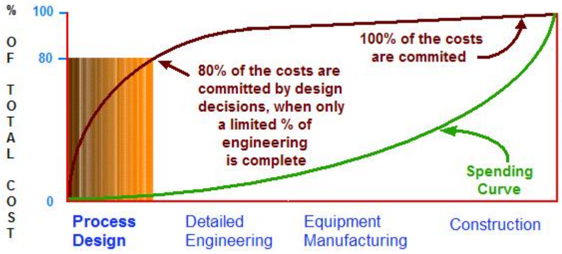


Figure 1 Project Expenditure Commitment Curve Vs Project Spending Curve (Source: Kinney et al 2004)

PERFORMANCE BASED ASSESSMENT

Growing requirements for higher building energy performance presents building owners with the motivation to demand energy assessment throughout the building life cycle. Current prescriptive-based assessment techniques employed by design teams thwart this goal. Traditional prescriptive based assessment –with its imposition of adherence to codes and standards- hinder organisational and technological innovation in the building and construction industry. Inherent interactions between building systems and building energy performance are not analysed and measures for their combined optimisation rarely investigated. Initial building energy performance assessment is carried out at the design stage utilising various simulation tools. These simulations are carried forward to commissioning tests for further HVAC examination. If BMS systems are installed, they monitor and control building energy performance. However, they rarely provide any feedback on design decisions and the resulting energy reports provide limited design feedback. This calls for a new form of assessment technique that addresses higher levels of building efficiency over all phases of the building life cycle.

Performance-based assessment is a different form of building energy appraisal It provides decision makers with information to assess the consequences of each decision in a timely, cost effective and practical manner. This assessment method addresses the ends rather than the means requiring an integrated approach and encouraging closer co-operation between clients, engineers and architects promoting increased productivity and a project-wide scope. Viable low-energy solutions are proposed from the outset reducing the unsupportive fragmented behaviour of different design teams with proprietary missions for the building. A teamwork approach adopted at the outset of the project, incorporating low-energy cost-effective designs, is vital as it reduces the client’s net costs for the project. With this assessment approach in place, a progressive improvement in energy efficiency of the building stock is a feasible and realistic target.

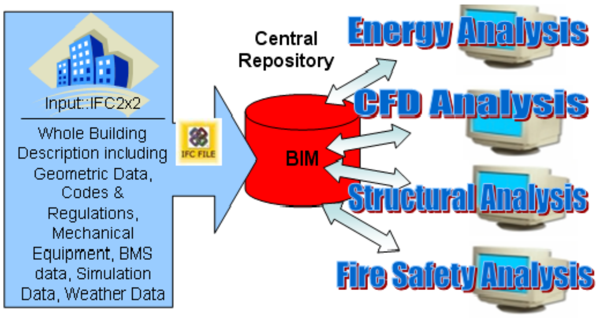


Figure 2 High Level Example Schematic displaying Interoperability Use

Assessment Framework

Linking the fragmented stages within the building life cycle and reduction of the user time for simulation models for each project phase, requires the ability to share and exchange information via integrated technological solutions. The framework information exchange network is referred to as the Building Energy Monitoring, Analysing and Communication (BEMAC) framework (O’Sullivan et al 2003). This non-proprietary integrated environment allows users to share data with other applications. The underlying schema utilised is the solution offered by the International Alliance for Interoperability (IAI), serving as an object orientated description of BIM data to ensure software interoperability in the building industry (IAI 2003). The latest version of the data model is Industry Foundation Classes Version 2 Edition 2 (IFC2*x*2). The IFC based objects allows structured and unstructured building information to be shared through an integrated data model. These data models allow each participant to employ tools specific to their needs without compromising or corrupting project data (Figure 2) presenting the ideal opportunity to execute building life cycle performance based assessment techniques.

BUILDING EFFECTIVENESS COMMUNICATION RATIOS

Historically, the most common performance metric for building energy consumption is ‘energy use intensity’ or kilowatt-hour per metre squared per year (kWh/m^2/yr). However this metric, with its mean or median value, tends not to be a discriminating metric for comparison of buildings (Federspiel et al 2002). Typically within the commercial industry, the owners and operators of these buildings are aware their buildings are expensive to operate, however they lack a tool to communicate or visualise the intrinsic energy efficiency of buildings over all phases of the building life cycle. This highlights a requirement for benchmark buildings displaying the intrinsic energy potential of hybrid buildings and stratagems for their performance appraisal.

In order to fill this void in the market place, a new set of discriminating whole-building metrics are required that are applicable across the entire building life cycle and capable of assessing the building without imposing adverse penalties. These penalties handicap certain facilities located in climate zones with large temperature ranges and imposed with obligatory building codes and regulations. In the authors’ opinions, energy benchmarking incorporating effectiveness ratios offers a viable solution. The effects of design decisions for the building may be utilised in comparison with the building’s benchmark values. These ratios quantify the energy performance of the building while factoring the thermal comfort of the occupants and catering for codes enforced by local environmental law. This allows the owner to increase energy savings without adversely sacrificing thermal comfort of the occupants. With these effectiveness ratios being applicable across the entire building life cycle, successes or failures of separate buildings can influence future design in a timely and cost effective manner.

Resource Data Warehouses for Effectiveness Ratios

In order to operate a building effectiveness ratio assessment of the building, two key resources must be employed. Firstly, a building management system (BMS) must be present. Their use will further the original goal of simply ‘monitoring’ HVAC components. These digital tracking systems are capable of storing data pertinent to the energy use for most HVAC systems and components within the building. Data may be stored in preset time steps and facilitate the trending and archiving. Secondly, a whole building energy simulation tool must be utilised. The energy simulation tool must be capable of modelling building heating, cooling, lighting, ventilating and include modular systems and plants integrated with heat balance-based zone simulation, multi-zone airflow, thermal comfort, photovoltaic systems and other energy flows as well as being capable of output in preset sub-hourly time steps.

Benchmark Metric

Data values elicited from this view of the simulation model act as best-possible values to adequately service the building. They offer the minimum amount of energy required to meet the basic functional and code compliant requirements of the building and are HVAC *systems independent*. Areas within the building that are to be serviced may be conglomerated into zones. The conglomeration process factors certain discriminating agents such as space use, natural lighting and other determinants. These zones are sized under certain conditions relating to the factors described above as well as the building’s location with regard to weather and codes regarding energy standards for the building and occupants. Other datasets required by the simulation engine include geometry & envelope characteristics, adjacent zones, infiltration rates, occupancy hours, thermal storage of building and all other information related to energy performance for the building. Because the climate, local regulations and space use are all factored into the benchmark, no adverse penalties are imposed. Once these zones are sized, all scrutinised systems are compared against these ‘benchmark metrics’.

Simulated Metric

By assigning spaces within the simulation model with proposed/existing HVAC systems, reproductions of the energy use by these mechanical systems are created for ease of relevant energy data representation and analysis. The HVAC system(s) modelled in the simulation directly emulate the HVAC system(s), installed or under consideration, by the design teams. These sets of data define the minimum amount of building energy utilised by the proposed or installed systems in order to adequately service the zones within the building. These values act as the ‘simulated metric’.

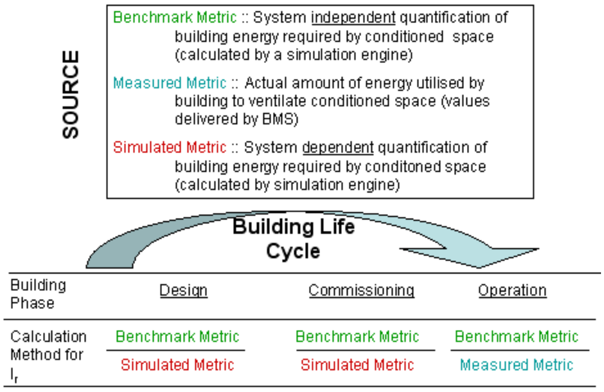
Measured Metric

Finally, data retrieved from the BMS offers the actual amount of building energy utilised in order to service the conditioned zones under scrutiny by the analysis team. These values act as the ‘measured metric’.

Idealised Effectiveness Ratio (I_r)

The Idealised Effectiveness Ratio (I_r) is the first of two building effectiveness communication ratios discussed in this paper. This ratio evolves as it steps through the building life cycle. The first phase of the ratio allows examination of various design decisions at the design and commissioning stages. Once the building is completed and under normal operation, a variation of this ratio is stored indicating a true measure of how efficient the building has performed. This ratio will be stored in a new generation of databases offering the ability to make allowances not previously possible. Analysis teams may scrutinise whole building design decisions in an unbiased environment where dissimilar buildings located in dissimilar climatic zones with dissimilar facility codes and regulations are all accounted and factored into the building energy assessment.

Calculation of I_r during the design phase of the building life cycle is computed by dividing benchmark metric values by simulated metric values for components under investigation (Figure 3). Values should range between 0 and 1 and higher values indicate levels of higher building energy performance. This allows design teams to assess the energy efficiency of myriad HVAC systems for the building. HVAC designs offering the highest energy performance may be selected from the series of designs available to the team. With the benchmark metric being unconstrained by facility use or global location, effectiveness ratios offer an unbiased environment for HVAC system appraisal and selection.



Benchmark Metric :: System independent quantification of building energy required by conditioned space (calculated by a simulation engine)

Measured Metric :: Actual amount of energy utilised by building to ventilate conditioned space (values delivered by BMS)

Simulated Metric :: System dependent quantification of building energy required by conditoned space (calculated by simulation engine)

Building Phase	Design	Commissioning	Operation
Calculation Method for I_r	Benchmark Metric Simulated Metric	Benchmark Metric Simulated Metric	Benchmark Metric Measured Metric

Figure 3 Calculating I_r through the Building Life Cycle

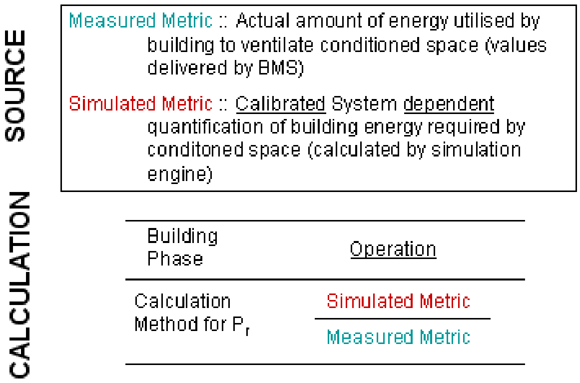
At the commissioning phase of the building life cycle, various temperatures, air-leakage (for ducts and whole building), system flow rate and humidity tests are performed. Relevant commissioning results may be input into the simulation model in order to calibrate the denominator (simulated metric) and a more evolved version of I_r may be calculated. Design teams can test a variety of set points for the system to increase the energy saving capabilities for the facility.

Once the building is occupied and under normal operation, values for the measured metric are retrieved from the BMS. Utilising these values as the denominator, I_r can be calculated and analysed offering an indication of the success (*or failure*) of the HVAC designs. (Note: the numerator (benchmark metric) remains standardised throughout each phase of building life cycle; it is the denominator that evolves.) Once I_r values for the building have been calculated utilising the ‘measured metric’, databases of these values may be populated in order to hierarchically rank the inherent performance of the building.

Performance Effectiveness Ratio (P_r)

After initial comparison of the building with various other buildings by the design team, the client may wish to enhance on-site HVAC performance. Values of I_r do not reflect to what extent the installed systems are performing; they merely rank the overall energy performance of the building. Baselining may be initiated, which involves a comparison of current energy use with historical energy use for the building. However, it is difficult to measure the extent of inefficient system performance due to changes in climatic conditions, zone operation, plug-in load (computers, desk lights, etc.), lighting levels, dirt in AHU filters, new ventilation requirements etc. This highlights a requirement for a *system-dependent* effectiveness ratio. The Performance Effectiveness Ratio (P_r) offers the capability to determine the energy saving potential of the installed systems within the building. Facility managers may wish to reduce operations costs for the building in a timely and cost effective manner. New operations management techniques (varying temperature set points, room use and occupancy schedules, plant on/off schedules, night cooling modes etc) may be incorporated and tested in the simulation model utilising this technique, resulting in an efficient form of operations management.

In order to prepare values for calculating P_r, the simulation of the building must be calibrated in order to accurately emulate the HVAC system. This involves the use of environmental sensors such as temperature and pressure probes. It is a more evolved version of denominator utilised for I_r during the commissioning stages. Once this is complete, the performance effectiveness ratio is calculated (Figure 4) by dividing simulated metric values by values elicited from the BMS (measured metric values). The simulation is run with weather input echoing conditions experienced by the actual system. This is vital for an accurate computation of the ratios. The benefits of new strategies tested in the simulation may be examined iteratively in a timely and cost effective manner. If these strategies are worthy of adoption, they may be incorporated into the building realising the energy efficiency potential of the building.



Measured Metric :: Actual amount of energy utilised by building to ventilate conditioned space (values delivered by BMS)

Simulated Metric :: Calibrated System dependent quantification of building energy required by conditoned space (calculated by simulation engine)

Building Phase	Operation
Calculation Method for P_r	Simulated Metric Measured Metric

Figure 4 Calculation of P_r

TECHNICAL DETAIL

The trial building for Building Effectiveness Communication ratios is the National University of Ireland, Cork's (NUIC) Glucksman Art Gallery (Glucksman 2004). This facility offers an ideal test-bed platform due to the complexity of the geometry within the building and the demand for tightly controlled environments for the preservation and safe keeping of a variety of art collections on show within the facility. Strict control of lighting systems, air temperature and humidity play vital roles in the facilities management of the gallery spaces.

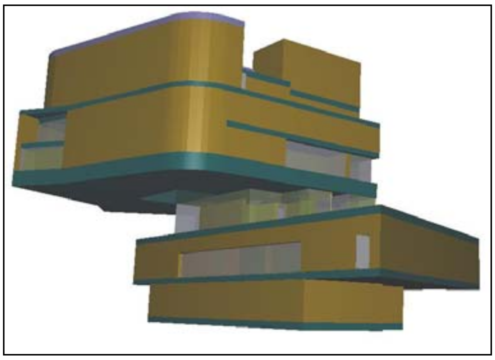
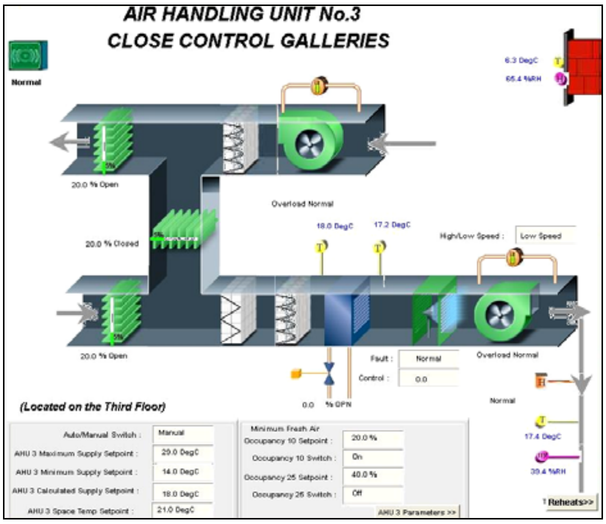


Figure 5 Geometric representation of the Glucksman Art Gallery, NUIC, Ireland, viewed from Solibri Model Checker

For the purpose of this paper, two rooms within the gallery being serviced solely by the one air-handling unit (referred to as 'AHU-3') are analysed. Tight space control of air temperatures and moisture content is required to avoid the deterioration of the exhibits while on display within the gallery. These spaces were required by the client (NUIC) to ensure the gallery would be able to obtain travelling exhibits of famous works, such as the Dürer collection, which was displayed during the official opening of the gallery.

Displacement ventilation air is supplied to the third floor gallery spaces at low levels and at low velocity, making use of the buoyancy effect to maintain comfortable and adequate conditions for both persons and artefacts alike in the occupied zone. The main source of heating and cooling is provided by a ground energy thermal transfer system. Two water-cooled chillers incorporating heat recovery loops generate both the chilled water at 6^{o}C and the heating water at 45^{o}C simultaneously. This is achieved as the heat recovery from the cooling process is fed directly into the heating circuits. AHU-3 is comprised of a return fan, mixing box, cooling coil, steam humidifier, supply fan and terminal reheat boxes. The HVAC systems utilised within the building are carefully adapted to match the requirements of each space while optimising the benefits of energy-efficient solutions (Burgess 2005).



High/Low Speed : Low Speed
Fault : Normal
Control : 0.0
Auto/Manual Switch : Manual
AHU 3 Maximum Supply Setpoint : 29.0 DegC
AHU 3 Minimum Supply Setpoint : 14.0 DegC
AHU 3 Calculated Supply Setpoint : 18.0 DegC
AHU 3 Space Temp Setpoint : 21.0 DegC
Minimum Fresh Air Occupancy 10 Setpoint : 20.0 %
Occupancy 10 Switch : On
Occupancy 25 Setpoint : 40.0 %
Occupancy 25 Switch : Off

Figure 6 Glucksman Art Gallery's BMS Graphical User Interface

Pertinent HVAC temperature, humidity and fluid-flow information is controlled and monitored by the BMS system.. The Glucksman Art Gallery's BMS is bundled with a Graphical User Interface (GUI) front end where facility managers may investigate parameters significant to the HVAC systems energy performance and efficiency (Figure 6). The BMS's storage facility containing temperatures and relative humidity levels allowing full investigation of the HVAC system.

The energy simulation engine utilised for the performance assessment is Energy**Plus** (US-DOE 2004). This whole building energy simulation package encompasses all the necessary simulation modelling attributes required for successful use of building effectiveness communication ratios.

EXPERIMENTAL ANALYSIS

For the purposes of this paper, and Idealised Effectiveness Ratio (I_r) is calculated to assess the performance and the energy performance of the HVAC systems installed in AHU-3. The building's design and commissioning phases are complete, therefore $I_{r\ (operating)}$ will be determined for post occupancy assessment of the building. This requires retrieval of related parameters from the BMS and benchmark values from the simulation model in order to generate a measured metric and a benchmark metric.

The first step in generation of these ratios begins with the geometric description for the simulation model (Figure 7 – orange area). Accurate representation of the geometry in any building results in enhanced model simulation, consequently it is important that the correct amount of attention is accorded the generation of the building envelope. ArchiCAD^{TM} provides the 3-D geometric description of the zones ventilated by AHU-3 (Figure 7). The ventilated zones are surrounded by spaces, which represent adjacent areas within the gallery. These 'dummy' spaces may be conditioned with ventilated air in the simulation model to emulate thermal conditions within neighbouring areas of the building (this ventilation air is completely separate from all AHU-3 components in the simulation model). The resulting geometric description is saved in the IFC2*x*2 format and investigated for errors using Solibri Model Checker^{TM}. This powerful inquiry tool prepares the model for intensive simulation by validation of building geometry. The resulting validated geometric representation of the building may now be instantiated in the BIM.

The HVAC simulation (Figure 7 - green area) begins with importing the building's IFC2*x*2 geometric description from the BIM and translating this intricate representation into Energy**Plus**'s input data files (IDF) utilising BSPro COM^{TM} server and its Energy**Plus** client. This middleware package simplifies complex IFC2*x*2 geometry definitions into a simpler form in order to communicate with non-CAD tools such as Energy**Plus**. HVAC description for AHU-3 and the ventilated air supplied to the surrounding zones instantiated utilising Energy**Plus**'s input text format of Input Data File (IDF) is now prepared. The simulation model can now be separated into two views and utilised for generation of the benchmark metric and a calibrated simulated metric (Figure 7 - blue area).

In order to generate benchmark metrics depicting the minimum required ventilation, a 'dummy' AHU similar to AHU-3 is instantiated in the simulation model. The simulated AHU contains a return fan, mixing box, cooling coil, humidifier, supply fan and terminal reheat boxes for the spaces similar to AHU-3 in the gallery. The benchmark's simulation model contains a simulated AHU due to the strict humidity control in the Glucksman Art Gallery. For buildings requiring only temperature control, it would be possible to elicit heating and cooling loads for the zone using purchased air. Purchased air is used in situations where the user wishes to study the performance of a building with an ideal system without having to instantiate plant or air loops. However, purchased air does not simulate humidity control as required in the Glucksman Art Gallery.

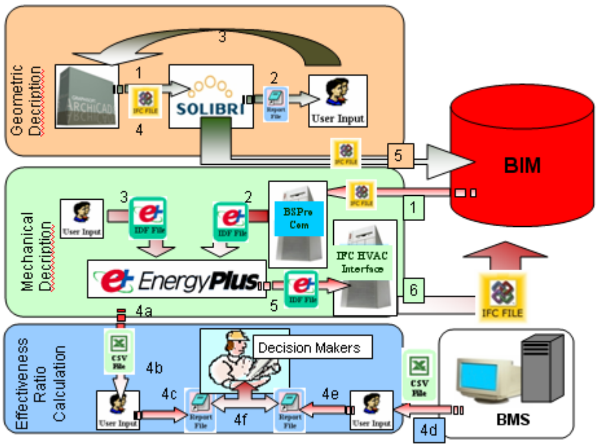


Figure 7 Instantiating the BIM and generation of building effectiveness communication ratios

Benchmark metrics act as 'the minimum amount of HVAC energy required to ventilate spaces, therefore this simulation model was investigated for minimum plant energy use. Certain parameters were flagged as 'excessive' energy wasters in the autosized AHU simulation. It was noted that high ranges in annual outdoor air moisture content leads to an expensive humidity control energy load. Thus, maximum fresh air intake into the system was entered as the amount of fresh air to adequately service max occupancy in the spaces with 12 litres of fresh air per second per person. Fixed volumetric flow rate in the AHU is excessive during low demand periods, therefore, variable air volume fans were utilised in the simulation model. Setpoints and other pertinent controls related to autosizing the AHU and its associated plants were assessed for retrieval of a minimum facility energy threshold.

In order to elicit data from the BMS (Figure 7 arrow 4d), users specify time period over which the building is to be assessed for each parameter. These data values displayed in the GUI are imported to excel files for data visualisation purposes. All pertinent energy performance calculations can be executed here.

Effectiveness Ratios for AHU-3 Cooing Coil

Figure 8 depicts values of $I_{r(operating)}$ over a three day period (*NOTE*: the plant is never turned off for safe care of the painted located within the space). These plots can be used to support building designers to determine the effectiveness of the design in the context of energy efficiency. Values of I_r lie between 0 and 1 with values approaching 1 indicating more energy efficient designs. As can be seen; an energy efficient cooling coil was selected to service these interior zones in the Glucksman Art Gallery. The average I_r value over the selected simulation period is 0.8 which demonstrates high levels of energy efficiency which expected by the design team.

Table 1 Design Data for E+ Energy Simulation Models

Design Conditions	**Values**
Zone conditions	21°C/50% rh
External Conditions	Cork Airport Weather File
Lighting Load	25W/m^2
Fresh Air Requirement	12 l/s/person
People	Max 25 persons/Average 14 persons (distributed)
Surrounding zones	Adiabatic condition with all surrounding zones @ 21^{o}C, except lower floor set @ 18°C

Table 2 Data Sources and Values for Calculation of I_r and P_r

Cooling Coil Load	**Source of Energy Data**	**Average Value (kW)**
$(Q_{cc})_{Benchmark}$	E+ system independent model	3.57
$(Q_{cc})_{Measured}$	BMS time averaged data	4.43

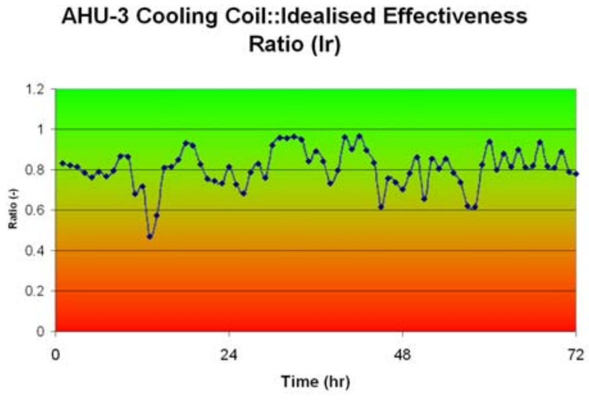


Figure 8 Graph depicting Idealised Effectiveness Ratio for cooling coil located in AHU-3

Visualisation of P_r supports the facilities manager in the efficient operation of the HVAC systems. Again, values approaching unity indicate management strategies realising the energy saving potential of the HVAC system. Due to time constraints, the authors were unable to generate an accurate system-dependent emulation of the installed system. However, it is envisaged that in generating higher values of P_r, the facilities manager can lower the values of cooling coil load. With these lower HVAC metric loads being realised, an updated version of I_r can be computed and these higher values depicting improved design efficiency may be stored in the BIM for outside scrutiny. Utilising this form of building energy assessment, an increase in energy efficiency for HVAC design and operation can be realised in a timely and cost effective manner.

CONCLUSION

Traditional prescriptive based building energy assessment is currently hindering technological innovation in the industry. Inherent interactions between building systems and building energy performance are not analysed and measures for combined optimisation rarely investigated. Performance based assessment offers design teams a framework addressing the ends rather than the means, requiring an integrated approach from the AEC&FM community that promotes strong links between product and process innovation throughout the building life cycle.

This paper proposes Building Effectiveness Communication Ratios; a performance based assessment methodology harnessing the appraisal potentials of building energy simulation models. These ratios offer the capability to scrutinise whole building design decisions in an unbiased environment unprejudiced against facilities located in dissimilar climatic zones, with dissimilar use and dissimilar building codes and regulations. With these effectiveness ratios being applicable across the entire building life cycle, feedback on the successes or failures of building designs can be visualised in a timely and cost effective manner influencing future design.

The Idealised Effectiveness Ratio (I_r) is the first of the two ratios and is applicable across the entire building life cycle. It allows design teams to investigate different designs from the outset and rate their success or failure on completion and occupancy of the building. The Performance Effectiveness Ratio (P_r) allows facility managers to investigate the energy saving potential of the installed systems and reduce HVAC energy costs for the facility. With this assessment approach in place, a progressive improvement in energy efficiency of the building stock is a feasible and realistic target.

FURTHER WORK

A complete assessment of the Glucksman Art Gallery is to be conducted. This requires a full description from ArchiCAD and Energy**Plus**. This assessment of the building will present the design team with a complete energy performance report providing feedback for four installed air handling units and various additional conditioning systems and measures installed in the Glucksman Art gallery.

A hierarchical breakdown of pertinent energy performance criteria will be instantiated in the BIM as outlined by Morrissey et al 2004 (Morrissey et al., 2004). The IFC2*x*2 schema offers the ideal framework for storage of these parameters offering a repository for future analysis and comparison.

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