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Building Effectiveness Communication Ratios (BECs): An Integrated ‘Life-Cycle’ Methodology for Mitigating Energy-use in Buildings

By

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A dissertation submitted to University College Cork
(UCC) in candidature for the degree of
Doctor of Philosophy

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“Discovery consists in seeing what everyone else has seen and thinking what no one else has thought.”

- Albert Svent-Gyorgi



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Abstract

Current building regulations are generally prescriptive in nature. It is widely accepted in Europe that this form of building regulation is stifling technological innovation and leading to inadequate energy efficiency in the building stock. This has increased the motivation to move design practices towards a more ‘performance-based’ model in order to mitigate inflated levels of energy-use consumed by the building stock.

A performance based model assesses the interaction of all building elements and the resulting impact on holistic building energy-use. However, this is a nebulous task due to building energy-use being affected by a myriad of heterogeneous agents. Accordingly, it is imperative that appropriate methods, tools and technologies are employed for energy prediction, measurement and evaluation throughout the project’s life cycle. This research also considers that it is imperative that the data is universally accessible by all stakeholders. The use of a centrally based product model for exchange of building information is explored.

This research describes the development and implementation of a new building energy-use performance assessment methodology. Termed the Building Effectiveness Communications ratios (BECs) methodology, this performance-based framework is capable of translating complex definitions of sustainability for energy efficiency and depicting universally understandable views at all stage of the Building Life Cycle (BLC) to the project’s stakeholders. The enabling yardsticks of building energy-use performance, termed I_r and P_r , provide continuous design and operations feedback in order to aid the building’s decision makers.

Utilised effectively, the methodology is capable of delivering quality assurance throughout the BLC by providing project teams with quantitative measurement of energy efficiency. Armed with these superior enabling tools for project stakeholder communication, it is envisaged that project teams will be better placed to augment a knowledge base and generate more efficient additions to the building stock.





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Acronyms

ADP	Apparatus Dew Point
AEC	Architectural, Engineering and Construction
AHU	Air Handling Unit
BACnet	Building Automation and Control NETWORKs
BECs	Building Effectiveness Communication Ratios
BER	Building Energy Rating
BLC	Building Life Cycle
BMS	Building Management System
BRE	British Research Establishment
BREEAM	BRE's Environmental Assessment Method
CO ₂	Carbon Dioxide
CSM	Constraint Set Manager
ECMs	Energy Conservation Measures
EEMS	Enterprise Energy Management System
EPBD	Energy Performance Building Directive
EU	European Union
EUI	Energy Use Intensity
DOE	U.S. Department of Energy
FM	Facility Manager
GETTS	Ground Energy Thermal Transfer System
GUI	Graphical User Interface
HVAC	Heating, Ventilation and Air Conditioning
IAI	International Alliance for Interoperability
ICT	Information and Communication Technology
IDF	Input Data File
IFC	Industry Foundation Classes
IP	Internet Protocol



I_r	Idealised Effectiveness Ratio
IT	Information Technology
LAN	Local Area Network
kWh	Kilo Watt Hour
LEED	Leadership in Energy and Environmental Design
LGHW	Low Grade How Water
LTHW	Low Temperature Hot Water
ODPM	Office of the Deputy Prime Minister
O&Ms	Operation & Maintenance Manuals
PC	Personal Computer
PM	Performance Metric
PO	Performance Objective
P_r	Performance Effectiveness Ratio
QS	Quantity Surveyor
RH	Relative Humidity
SEI	Sustainable Energy Ireland
SMC	Solibri Model Checker
TCP	Transmission Control Protocol
TMY	Typical Meteorological Year
UK	United Kingdom
US	United States
VAV	Variable Air Volume
WAN	Wide Area Network
WWW	World Wide Web







Chapter 1

Introduction

Chapter 1 discusses the research motivation behind the development of the proposed methodology. It outlines the societal, legislative and economic bases as to why management techniques (employed within the building stock) must mitigate energy-use. Finally the chapter investigates many of the popular sustainability assessment frameworks available in the marketplace today and examines why they are having an inadequate effect on operational performance of the building stock.

“One who asks a question is a fool for five minutes; one who does not ask a question remains a fool forever.”

- Chinese proverb



1.1 Background

Acting in a sustainable manner requires that the satisfaction of current human needs does not compromise the needs of future generations (Zimmermann et al. 2005). Energy fuels the world's economy and is the essential ingredient for the continuation of civilisation. Accordingly, the sustainability of world energy supplies is being recognised as one of the greatest challenges faced by humanity.

Unfortunately, our way of life threatens the planet on which we reside. The Earth is unique within our solar system; it is the only planet we - as human beings - are capable of occupying without outside aid. However, humanity's tenure on the earth is facilitated by a *delicate* balance of greenhouse gases moderated by the earth's atmosphere and its inherent natural ability to maintain life (Langston 2001). Therefore, it is vital that society's needs do not overtax the earth's bio-diversity and ecological balance.

Unfortunately, decades of industrial and economic activity have resulted in elevated levels of energy-use. The practice of burning fossil fuels to provide the majority of the earth's energy supply is causing the release of the main greenhouse gas: CO₂. Greenhouse gases cause the earth to heat up by trapping the sun's heat within the earth's atmosphere, resulting – in part – in the unsolicited shift in weather conditions (Gaterell and McEvoy 2004). The result of these actions is a disruption in the 'delicate balance' required by humanity to reside on this planet.

Evidence of these effects surrounds us. The 1990s was the warmest decade on record, snow cover is down 10% in the past 40 years and the five warmest years since the 1660s (the earliest weather data on file in the UK), occurred during the late 1980s and 1990s (UK-Government 2003). These increases in global temperatures will have many disparate impacts on a myriad of industries.

The outlook for the buildings industry includes problems with overheating, reduction in cost-effectiveness of design solutions and the introduction of cooling loads (Gaterell and McEvoy 2004). It is imperative that current energy-use levels are reduced to curb the rate of climate change so that effective building design solutions today remain effective solutions tomorrow.

There has been a strong argument for a switch to clean renewable sources of energy. However the switch to solar, wind and hydro powered generation of energy is slow in



coming and requires intensive capital investment. A pragmatic approach is required as there is little benefit in over-investing in capital-intensive renewable sources of power which would not be required if we can achieve higher levels of energy efficiency and reduce our total energy consumption (Garbutt 2003).

An additional concern for government agencies is our susceptibility to volatility in energy producing countries (UK-Government 2003). Given the recent (plus current) energy crises, depending on outside reserves of energy is no longer a luxury to be enjoyed during favourable economic times. Within the US, energy prices are rising significantly faster than inflation (Mahling and Lehman 2005). Many developed countries within the EU are net importers of energy (for instance, in 2004, Ireland import 87% of its energy (Howley et al. 2006). If present trends continue, dependence on outside sources of energy is estimated to increase from 50% today to 70% in 2030 (EU 2000). As this rate of energy consumption continues unabated, vulnerability to political and economic instability in the supplying countries increases (Dix 2003; Gaterell and McEvoy 2004).

Energy production seems unlikely to be curtailed within international borders as government agencies strive to balance (1) the economic needs of society and (2) proprietary political pursuits against the mitigation of CO₂ production. A worldwide obligation – derived from the Kyoto Protocol agreement – to reduce CO₂ emissions by 6.5% by 2008-2012 compared to 1990 levels is a driver for much of the worldwide energy policy legislation (Lenschow 2001). Even within countries unlikely to ratify it, there seems a recognition that energy efficiency must improve. Unfortunately, despite this ‘recognition’, the UK and Sweden are the only EU countries have met their obligations to date. It is estimated that Denmark, Spain, Ireland, Austria and Belgium will exceed 2010 target emissions by 20% or more (Fletcher 2004).

Simply reducing energy production without placing contingency plans for alternative solutions to satisfy of society’s needs would be disastrous and short sighted. High-end energy consumers such as buildings, street lighting, electricity supply, etc. just can’t be ‘turned off’. However, reducing society’s requirement on energy reserves is a feasible aim. The contribution made by our building stock is seen as pivotal to achieving sustainable development (Hui 2002).

Buildings are serial consumers of earth’s energy reserves. We spend the majority of our time within the confines of buildings. Keeping the building stock adequately heated,



cooled and ventilated draws on vast quantities of energy. Within the US, buildings are responsible for 65% of all electricity production and produce 30% of all greenhouse gas emissions (Wells 2002). In the UK, buildings are responsible for 50% of annual CO₂ emissions (Best et al. 2003). Within Ireland, it is estimated that building services account for 43% of total EU energy consumption (Dix 2003). Alarming, building energy consumption seems to be rising (Ellis and Mathews 2002). Consequently, there is an emerging interest in adequate *energy management* strategies and assessment frameworks for the building industry. The US National Energy Foundation believes a change in *behaviour*, not technology, is the key to tackling climate change. Tim Lunel, chief executive of the foundation is quoted as saying (Pearson 2005):

“We need initiatives that result in action now at the individual community, business and country level, not the promise of technological breakthroughs in the future.”

The following research is guided by this viewpoint and proposes a pragmatic framework for the assessment of holistic building energy-use. There has been a good deal of research carried out in the area of performance-based building assessment (Cole 2001). This thesis aims to:

- 1) build on existing performance-based toolkits;
- 2) provide a pragmatic framework encapsulating sets of consensus-based sustainability indicators; and
- 3) present the environment required for this form of building evaluation.

This performance-based assessment methodology is applicable at all stages of the building life cycle (BLC). It factors thermal environment required by occupants, provides a yardstick of building energy-use efficiency and ultimately delivers a new language of communication for all project participants. It is envisaged that through effective use of the proposed framework, a more proficient management of energy-use within the building stock is a realistic and feasible goal.



1.2 Building Sustainability Performance Assessment

Many voluntary assessment frameworks and schemes have emerged in recent years in an effort to qualify the sustainability of buildings (Hui 2002). These assessment schemes are changing rapidly to assess hybrid design solutions offered by design teams (Chau et al. 2000). In general, these environmental schemes assess the sustainability of a facility based on:

- 1) Emissions (greenhouse gas production);
- 2) Surrounding habitat releases;
- 3) Waste management;
- 4) Utilisation of non-renewable resources;
- 5) Utilisation of renewable resources.

1.2.1 Need for Energy-use assessment

Given the requirement to decrease society's dependence on energy reserves, Demand-Management measures are beginning to take a more central role in building projects, (Cole 1999; Gaterell and McEvoy 2004). Despite stipulations of effectiveness by clients, many air conditioning solutions are over-sized or improperly installed, leading to inflated energy consumption (Geller 2002). Within the US, building services such as lighting, heating, ventilation, air conditioning, public health systems and lifts typically account for 30-40% of total construction costs in commercial buildings and around 36% of total energy consumption. The energy-use in commercial buildings accounts for space heating accounts for 47% of total energy consumed (Asimakopoulous et al. 2001). Additionally, it is estimated that HVAC systems alone account for 10% of all electrical energy consumed in the world (Rousseau and Mathews 2003). It is widely accepted that buildings are not performing as well as expected during the pre-design and detailed-design stages.

In many of the popular sustainability assessment toolkits, efficient utilisation of *building energy* is a key element in the project evaluation (Hui 2002). This is significant as it highlights 'effective building energy-use management' as one of the *key* focus points for



consideration during all stages of the BLC. Unfortunately, significant shortcomings encapsulated within many of the popular assessment frameworks will not solve the problem (as will be discussed in Section 1.5). This highlights a requirement for a building assessment toolkit capable of reducing building energy consumption while maintaining comfortable indoor conditions.

1.2.2 Current Energy Regulatory Systems

Energy policy and legislation represents the linchpin for a more sustainable urban development (Geller 2002). In order for government bodies to preside over an energy-efficient building stock; control and guidance of building solutions at various stages of the BLC is required. Common policies for energy regulation include mandatory codes and standards, voluntary codes and standards, incentive schemes and energy labelling (Langston 2001). These policies may be qualified under two distinct definitions; prescriptive-based assessment and performance-based assessment. The following two subsections define both of these assessment contrasting policies.

1.2.2.1 Prescriptive-based Regulations

Generally, existing building codes are prescriptive in nature (Hui 2002). Prescriptive-based assessment techniques encapsulate mandatory codes and standards; voluntary codes and standards; guidelines; and incentive schemes. They act as quantitative vehicles driving energy efficiency practices. Prescriptive codes tend to be easy to check and generally specify minimum requirements, design methods or design standards for which the building must comply. A simple example of a prescriptive code would be prescribing the insulation level in walls for the building envelope.

Unfortunately, when employed as a driver for design process, prescriptive codes carry an inherent key disadvantage as these guidelines often substitute as *societal acceptable levels of performance for buildings* (Bergeron and Bowen 2001). By merely establishing a level of risk (or performance), there is an implicit message of an acceptable solution resulting in the legislation *stifling* any of kind of performance optimisation, innovation and technological advancement within the industry (Wallace 1995).

An additional shortcoming with prescriptive building industry legislation is the disparate nature of the environments involved; the evolution of the building industry does not flow



at the same rate as the inertia associated with the legislative process. Amendments to these prescriptive standards are often laden with opposition from the industry which is compounded by time-consuming administrative procedures (OECD 2003). Given the slow nature of change within the law, prescriptive codes and standards tend to become obsolete quickly due to continually evolving sets of tools, methods, technologies and information available to design teams to optimise building solutions (Beller et al. 2001).

1.2.2.2 Performance-based Regulations

Building regulatory systems around the world are gradually evolving in response to the changing political will. The trend is a transition from prescriptive-based codes and regulations in preference to a more performance-based environment (Emmitt and Yeomans 2001). Performance-based assessment frameworks act as a trade-off set of regulations for a building, emphasising an approach that addresses the ends rather than the means (CIB 1997). These regulations distinguish themselves from their prescriptive counterparts by specifying goals and referencing sets of criteria that can be used to assess whether the objectives have been met (Beller et al. 2001; Bergeron and Bowen 2001). This results in building assessment as a whole as opposed to the individual conformity of components.

Performance-based codes generally include one or more acceptable solution(s) which are deemed to deliver the target performance (Bergeron and Bowen 2001). Acceptable solutions are considered to be a set of provisions which – when met – will deliver the target performance as intended by the qualitative and quantitative specifications of the legislation. Acceptable solutions often establish the baseline of energy-use against which, innovative designs or project specific designs are compared to determine compliance.

The strength of performance-based codes lies in their allowance for *flexibility in design*. By not specifying exact methods or materials to be employed in order to achieve prescribed targets, optimal solutions are proposed from the outset. Thus a *trade-off* approach can be operated so that a combination of measures can be employed and optimised within a constraint budget of cost, environmental impact and energy-use. This form of legislation encourages innovative solutions that reduce energy consumption and is a major reason for governments adopting this form of building codes and regulations (Brochner et al. 1999; Bergeron and Bowen 2001).



It should be noted that no single model suffices for every country, however most systems follow a similar framework and cite common performance metrics and engineering methods. It also encourages a greater participation among the project team to generate optimal energy efficient solutions for the project. It is envisaged that this teamwork or collaborative design approach will aid design teams reap enormous benefits for the good of the client and the environment. The proposed methodology adopts this performance based approach for assessment of building energy performance throughout the project's lifecycle.

1.3 Limited Life Cycle Energy Assessment

Building energy-use assessment toolkits are generally employed in a small fraction of buildings. In most cases these tools are only employed during the detailed-design stage or during a retrofit analysis. This is due to the fact that decisions made during the early stages of design have a large impact on the performance of the building, decisions made at later stages merely generate marginal performance improvements (Gratia and Herde 2002).

Unfortunately, it is widely perceived within the AEC&FM community that actual operations of many buildings is not performing as efficiently as envisaged during design stages (O'Sullivan et al. 2004). This highlights a lack of operational assessment of building energy-use performance. This thesis delineates an energy assessment framework applicable across the entire BLC provides a direct feedback loop for solution appraisal.

Unfortunately, there are many barriers impeding the adoption of BLC energy assessment by the AEC&FM community. These barriers are discussed in the following subsections.

1.3.1 Building Industry Teamwork and Communication

An efficient building stock can only be achieved if all links within the demand and supply chain work cooperatively. However, the building industry has a poor reputation for communication among individuals, organisations and across project phases. This is especially true during the pre-operation stages of the project life cycle (Emmitt et al. 2003). The fragmented nature and lack of co-ordination within the industry that does not support holistic energy-use assessment may be attributed to many factors:



- 1) Transition of performance-based assessment through BLC stages requires rich sets of building information. In general, design teams utilise proprietary tools that are unable to communicate with each other. The resulting duplication of building data is a labour intensive practice and is both error prone and time consuming (Bazjanac 2001). Given the current design process environment, undertaking holistic assessment of the building requires *experience* with huge data warehouses from many disparate media. These technical processes mandate additional expertise within the design team fuelling design process costs.
- 2) Energy-use assessment tools for buildings *require* data sets describing tangible and intangible information. However, during the early stages of planning, data streams are unstructured and incomplete (Mourshed et al. 2003). With poor communication and co-operation already present during design stages, adequate assessment of the building energy-use is considered to be infeasible.
- 3) Many buildings are handed over after the commissioning phase with very limited (or often inaccurate) data sets of information and no overall communication of design philosophy. If a facility management team desire a holistic simulation of the facility, a survey of the building is required in conjunction with references to the Operations And Maintenance (O&M) manuals. Facility managers may not have the funds to launch surveys of this magnitude.

1.3.2 Application Stage for Assessment Tools

Existing sustainability assessment toolkits target specific stages of the life cycle for the building. Widely used (and industry accepted) sustainability assessment drivers such as LEED used primarily in the US and Canada (Section 1.5.1) and BREEAM used primarily in Europe, Asia and Australia (Section 1.5.2) target the design stages of the life cycle. The disadvantage of having assessment frameworks targeting specific stages of the BLC lies in the lack of any *feedback* or *feedforward* inherent in these assessment frameworks. Additionally, the building's rating (or label), generated by the toolkits, cannot be unambiguously tied to any specific design decisions. The by-product of this deficiency is that current assessment methodologies lack the ability to educate the marketplace on the impacts of specific design decisions. Each building is acting as a '*prototype*', discarding



valuable information capable of leveraging beneficial lessons for consideration in the next building project.

1.3.3 Project Budget

A financial budget is contained in any building design proposal for a facility. The complexity of whole building assessment tools lends an inflated time-cost issue for BLC energy-use evaluation. The period of analysis required to prepare the input information for performance assessment (Section 1.3.1) and assess the output for current toolkits is widely considered to be too costly. Often, the client – who sets the budget – is unaware of the benefits available through regular energy assessment (discussed in Section 2.2.4).

1.3.4 Prescriptive-Based Codes

The existing domination of prescriptive-based regulations is resulting in adverse effects (Section 1.1.2.1). Compliance with these quantitative codes is substituting as an acceptable energy efficiency assessment of the design solution (Papamichael and Pal 2002). Scrutiny of whole-building energy performance by individual components that adhere to these codes is considered to be *superfluous*.

1.3.5 Technical Ability

Incorporating a whole building assessment of a project is not an easy undertaking. It requires team members to understand that a building is in fact a *dynamic* entity rather than a static product. Complicated software programs are intrinsic in analysing dynamic entities and potential users require adequate degrees of expertise in many disparate analysis tools. In the industry's current environment, project members lack the technical ability or training (or even educational background) to utilise energy-use assessment tools adequately for achieving high levels of building energy performance.

This can be explained through viewing the history of the industry. In a sense, the building industry has been around since the beginning of humankind; from Stone Age huts, to medieval castles to today's skyscrapers. Unfortunately history tends to highlight a very slow evolution of processes. People tend to be amazed when they learn of the similarities in how a building was built a thousand years ago and how they are built today. But one



should not marvel at how ‘ahead of their time’ our ancestors were, and instead question how ‘behind the time’ current practitioners are.

Advancements in domains effectively utilising Information Technology (IT) surround us. High profile examples include space exploration, mach speed travel, etc. However, society still has not advanced the building industry’s processes much further than the ‘drawings on tilted boards’. The generation of drawings on AutoCAD is nothing more than a migration of the archaic ink plots onto the computer using auto-hatch and ‘layer’ functionalities. Project management schemes do attempt to pool information together, however, in spite of this, the building’s processes continue to be broken down into fragmented islands requiring mountains of paperwork that often gather dust as the facility ages (O’Sullivan et al. 2004).

There are many disparate reasons for the industry’s lethargic evolution, but the education facilities which supply the industry with personnel may have to shoulder some of the blame. Potential workers in the industry are moulded and educated to fit into ‘peg-holes’ in order to continue these outdated processes and neatly fit into the *modus operandi*. Inadequate emphasis is placed on communication and teamwork during early education days.

This adverse issue is compounded by the fact that, potential workers in the industry are often coerced towards *expediting the process* rather than improving the product. Calculations that were historically done by hand have migrated onto massive Excel spread sheets in an effort to generate results faster. Accordingly, project members continue working as individuals and are unprepared for work within the ‘team’.

1.3.6 Marketplace Interest

Utilisations of tools that improve the product, but prolong the process, are perceived as superfluous during the design stages (for reasons discussed in Sections 1.3.4). Design teams are under significant pressure to deliver their solutions in a timely and cost effective manner. Life cycle performance evaluations take time and as a result fuel project costs. This is not an ideal situation for an industry steered by practices of lowest cost tendering. Design teams simply cannot afford to use these intensive tools as they will lose out in the bidding war at proposal time.



Often, building stake-holders mistakenly view a building as a static entity and blindly assume all energy-related issues were addressed at design time. There is no realisation that performance can be increased if building stakeholders evaluate the *operational* performance of the building.

As a result, only a specific stipulation for evaluation of building performance throughout the BLC from the client *or* an additional requirement in the building codes and regulation would alter the marketplace interest. Fortunately, the evaluation of performance at design *and* operational phases will become mandatory within the EU (Section 1.4.1). If adopted suitably, these sets of codes will alter marketplace interest.

1.4 New Directives and Regulations

Governments tend to have an extremely limited influence on external sources of energy. However, they *do* have control over the potential *use* of the energy (EU 2000). Political pressure to reduce energy consumption often proves *unpopular* and *strong drivers* are required in order to be effective as commercial realities are frequently unsupportive to energy saving desires (Dix 2003). Within the building industry, capital costs drive the decision making processes during the design, construction and operation stages. This has led to low capital cost buildings but also to low performing buildings which often results in high operation costs (Clements-Croome 2003). The challenge for government agencies is to promote a more energy efficient building stock in a cost effective and environmentally-responsive manner. Generally, clients are often only interested in building aesthetics, structural integrity and other architectural features. However, if stakeholders face penalties due to inefficient buildings, the design process will be driven by a more energy conscious outlook throughout the BLC.

A number of policy documents from the EU have highlighted the potential improvements in the built environment given adequate policy and directives (Gaterell and McEvoy 2004). The following subsections discuss the European efforts in the past four years and Californian legislation that has guided the building stock towards a more sustainable future.



1.4.1 European Union – Energy Performance Building Directive (EPBD)

The EU seeks to spawn a building stock that operates at a lower energy cost without sacrificing performance and has targeted greenhouse gas reduction as one of its key objectives. Research within the EU has indicated an *energy efficient building stock* could reduce CO₂ emissions by 22% (Council 2004). In order to address this key issue, the European Parliament implemented the Energy Performance in Buildings Directive 2002/91/EC (a *performance-based* legislation), commonly referred to as the EPBD. By January 2006, building owners within the EU states will have to quantify the energy usage of their facilities against benchmarks set by government agencies throughout the BLC. Facility owners will receive labels with energy ratings for their buildings which must be displayed at the entrance to the buildings.

This directive is simple and clearly written. It not only focuses on new buildings, but also on the redevelopment of old and dilapidated buildings in the urban renewal process. The impacts from the legislation are likely to affect 160 million buildings throughout the EU (Dix 2003). The buildings covered by the directive include residential buildings, offices, wholesale and retail trade, hotels, restaurants, schools, hospitals, sports halls, indoor swimming halls, etc., although it excludes industrial buildings.

The goals of these labelling strategies include:

- 1) removing barriers to innovative and green building designs;
- 2) coercing the marketplace into becoming more energy efficient and sustainable by empowering the building owners to insist on more energy conscious design practices;
- 3) promoting an energy efficient building stock;
- 4) creating differentiation among buildings during the sale and resale process by communicating the energy saving potential of the facility.

No single model or framework is capable of addressing every country's requirements (Tubbs 2003). The regulations set down in the directive are open for interpretation and proprietary performance-based legislation is being implemented by individual member



states. Two member states' sets of regulations pertinent to energy policy in buildings are discussed.

1.4.1.1 U.K.

Recent legislation introduced in the UK has highlighted the government's concerns about inadequate energy management in the building sector (Gaterell and McEvoy 2004). The new building regulations have put forward an aim for a 25% reduction in CO₂ emissions based on 2002 levels (ODPM 2005). The UK's white paper, published in early 2003, sets policy goals designed to aid development of a low carbon economy through environmentally sustainable, reliable and competitive energy markets. The goals cover limiting the UK's susceptibility to interruption of energy supply from foreign suppliers, reduction of greenhouse emissions and updating the existing infrastructure. One of the key goals set out by the government is a 60% reduction in the UK's CO₂ emissions by 2050. This goal will only be possible through innovative thinking for all aspects of energy-use. Efficient building *design* and *management* has a large role to play in assisting the realisation of these goals.

Buildings within the UK must comply with Part L of the building Regulations (ODPM 2005) at both design and operation stages. The mission for this part of the regulations is to produce a building stock that requires low energy input to maintain adequate levels of thermal comfort. The proposed changes to Part L will incorporate the issues highlighted within the EPBD. Among other things, this includes requirements for a method to calculate the energy performance of buildings (new and old). Under the provisions of the directive, the energy performance of a new building is calculated as a whole. A reference building that complies with the regulations is included and meant for appraisal of the building under evaluation. A predicted emissions method would become the standard means of compliance with Part L.

As this is a performance-based legislation a 'trade-off' solution can be employed by design teams. In some buildings, the designer may wish to concentrate on improving the envelope efficiency by including more insulation and optimal windows. In other buildings, designers may wish to concentrate on the building services and efficient lighting. The detailed approach depends on the structure of the calculation methods currently being developed in the building regulations. Designers will have the flexibility



to choose the areas within the building that are best-case solutions for increased efficiency in order to elicit a ‘sustainable’ addition to urban development.

The British Research Establishment (BRE) is currently developing a tool, commissioned by the ODPM, to demonstrate a building’s compliance with the proposed regulations. The tool, known as the Simplified Building Energy Model (SBEM), is based on the National Calculation Methodology. However, as self-described in the title, it is a ‘simplified’ methodology. It is accepted that many building’s energy-use characteristics may not be qualified by this simplified qualification tool. Accordingly, energy performance evaluation for these facilities can be carried out by more sophisticated energy simulation packages peripheral to this tool (Davidson 2005).

1.4.1.2 Ireland

The control of Irish buildings falls under the jurisdiction of the Building Control Act 1990 (OAG 2005). However, the design process for HVAC strategies is mainly driven by British and Europeans standards as, quite often, there is an absence of any local legislation driving mechanical design. However, the EPBD does require that Ireland makes amendments and additions to its current set of regulations. At this time, Ireland has prepared a draft action plan which was published on 27th April, 2005 as a document for public consumption. It was prepared by an Inter Departmental Working Group, comprising senior officials of the Department of the Environment, Heritage and Local Government (DEHLG), Department of Communications, Marine and Natural Resources (DCMNR), and Sustainable Energy Ireland (SEI), with SEI providing all secretariat services.

The changes in building regulations are expected to impact on over 150,000 sale or rental transactions per year in the residential market within Ireland (SEI 2005). Within the draft action plan, Ireland will implement the provisions of the EPBD between January 4th 2006 and January 4th 2009. The main areas of focus will be:

- 1) the labelling (and rating) of newly constructed buildings, existing buildings (when buildings are let or sold) and public service buildings;
- 2) increasing the energy efficiency of certain classes of boilers and heating installations; and



3) regular inspection of air-conditioning systems.

Although not complete, relevant implementation proposals are highlighted in the draft plan. The provision gaining the most interest in the marketplace is related to the ‘labelling’ of a building. Building Energy Rating (BER) certificates (effectively an energy label) at the point of sale, rental of a building, or on completion of a new building will be accompanied by an ‘Advisory Report’ setting out recommendations for cost-effective improvements to the energy performance of the building. However, these reports are merely recommendations, they are not compulsory. It is envisaged that the existence of BERs will alert the public to the scope within the industry for improvement of the energy efficiency of the buildings stock and reduction of operational costs. For purchasers, it will create differentiation within the building stock between energy-inefficient ‘dinosaurs’ and energy-efficient ‘green buildings’.

1.4.2 California Title 24

One of the most comprehensive efficiency standards is the US’s California Title 24 (Title24 2006). This set of “Model Energy Codes” for efficiency standards in lighting and HVAC was developed in order to set minimum commercial building energy codes for alterations and additions of commercial and non-commercial buildings.

In order to stay up to date with the latest marketplace technologies, the standards are updated periodically and it is estimated that these sets of standards have saved more than \$56 billion in electricity and natural gas costs since 1978 and it is expected to save an additional \$23 billion by 2013. A recent report considers that for each year of construction activity (in both new and renovated facilities) the regulations contained within Title 24 are estimated to reduce the growth in electricity by 479 GWh and to reduce the growth in peak demand by 182.3 MW (CEC 2003). Additionally, natural gas use is expected to be reduced by 8.9 million therms. The same report expects the savings to accumulate as the regulations affect each subsequent year of construction (after two years the savings would double, triple after three years and increase tenfold in the tenth year). Such contributions by legislation are vital if worldwide energy dependence by the building stock is to be curtailed.



1.5 Current Building Assessment Tools

Given the increased interest in building performance, there have been substantial efforts in recent years in the design and enhancement of urban development sustainability appraisal toolkits (Chau et al. 2000). While these tools differ in the scope of their assessment, energy-efficiency usually forms a key element in the appraisal process (Hui 2003). In order for these tools to communicate the building assessment unambiguously, comprehensive sets of performance indicators must be expressed to suit local needs. Some examples of the frameworks include:

- 1) rating buildings based on sets of criteria (e.g. Assessment frameworks incorporating complex Microsoft excel macros);
- 2) measuring actual performance of the building (e.g. BMS systems); and
- 3) predicting the performance of buildings (e.g. energy simulation tools).

The remainder of this subsection discusses some of the voluntary national and international toolkits that are widely used within the industry. Many of these frameworks have many invaluable capabilities. The research carried out (and discussed in subsequent chapters) builds on their strengths and proposes a new kind of performance-based assessment presented which addresses their weaknesses.

1.5.1 LEED

The LEED (Leadership in Energy and Environmental Design) green building rating system is a *voluntary* sustainability assessment for new and existing building providing coverage to environmental, social and economic issues deemed to be relevant to sustainability (LEED 2005). Developed in the US, this assessment tool was a critical development within the industry as it ended the practice of project teams paying lip service to sustainability without any quantitative proof. It produces an unbiased assessment of the ‘greenness’ of a project and increases consumer awareness of the rigours involved in building a sustainable project. Ultimately, the LEED rating system offered (and still offers) “concrete guidelines for the design and construction of sustainable buildings for a liveable future” (Wells 2002). The development of this tool



was significant step forward for reducing the environmental footprint left by the building stock.

The LEED rating system assesses the holistic sustainability of a project under five abstract headings which include:

- 1) sustainable sites;
- 2) water efficiency;
- 3) energy & atmosphere;
- 4) materials & resources; and
- 5) indoor environmental quality.

Within each of these categories, prerequisite requirements and optional credits are awarded to the building. These prerequisites and credits are elaborated with descriptive statements related to its intent and advice on technologies/strategies that can be incorporated into design solutions to achieve the particular goal (Hitchcock 2003). Different levels of green building certification are awarded based on the total credits awarded with a view to achieving the ultimate goal of a five star building. It is significant to note that out of a possible 69 points available, 14 of these come under the heading of ‘energy data’.

LEED has many inherent benefits which make it an extremely robust tool. It provides a holistic rating for the building whereby the whole building is assessed in one ‘all-encompassing’ rating. The rating itself is extremely easily understandable by those not directly involved in the industry.

Unfortunately, LEED also has many weaknesses:

- 1) There is a large associated cost with undertaking a LEED assessment as it is not directly part of the design process.
- 2) Although, LEED claim the tool has application through the BLC, this framework provides more of an asset rating than a performance rating.
- 3) There is no communication of design philosophy.
- 4) There is no update in the LEED ‘rating’ for the building regardless of a change in space use, leading to poor or mismanaged operational strategies.



1.5.2 BREEAM

For over a decade, BRE's Environmental Assessment Method (BREEAM) has been used to qualify the sustainability of both new and existing buildings (BREEAM 2005). Based in the UK, but widely adopted in the rest of the world, this voluntary sustainability toolkit covers a wide range of environmental issues. These issues include:

- 1) policy management;
- 2) energy-use;
- 3) health and well being;
- 4) transport,
- 5) land use,
- 6) ecology,
- 7) materials; and
- 8) water.

During the sustainability evaluation; credits are awarded in each of the areas according to performance. A set of environmental weightings then enable the credits to be summed in order to attain the building's BREEAM rating. BREEAM covers a range of buildings including offices, homes, industrial units, retail units and schools. Additional facilities require a bespoke version of BREEAM. However, an interfusion of these facilities can cause difficulties in retrieving accurate ratings for the facility.

A BREEAM assessment is typically undertaken externally before a facility goes to tender. However, due to its inherent robustness, high international profile and ease of use, design teams utilise the rating as a 'checklist' for receiving the prescribed rating. It can act as a form of checker for the environmental impacts of design decisions. Figure 1-1 displays a typical distribution of assessment undertaken by a design team when utilising BREEAM as a driver for sustainability.

BREEAM is widely adopted and has become the industry standard 'approval' of sustainable buildings in many countries. Thus, it is significant that out of a total of 1,046



possible points, energy-use related issues come to 208 points; highlighting the essential role of efficiency of energy-use in a sustainable building.

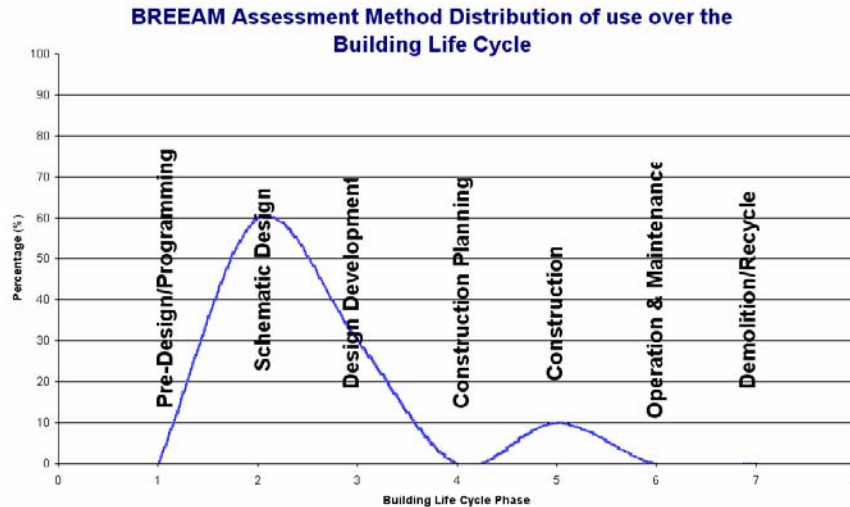


Figure 1-1 – A typical distribution of BREEAM application for steering a sustainable outlook for a building

The toolkit’s weaknesses mirror those described for a LEED assessment (Section 1.5.1). The key issue is that BREEAM has no role to play in the operation and maintenance of the building (Figure 1-1). The assessment framework becomes disconnected once the building is handed over the client and it becomes difficult to relate the myriad of specific design decisions to the overall rating for the building.

1.5.3 CalArch

CalArch is a web-based tool for benchmarking whole-building energy-use for commercial facilities located in California, USA (CalArch 2005). Its development is funded, in part, by the California Energy Commission Public Interest Energy Research program under the High Performance Commercial Building Systems project (HPCBS 2005). The tool provides a simple method to access information relevant to buildings located in California.

It is an interactive toolkit located on the World Wide Web (WWW). On completion of a questionnaire, users receive a feedback report which graphically depicts how the



building's Energy Use Intensity (EUI) compares with a sample set of similar buildings and reports the percentage of buildings in the database operating with lower EUI levels.

Cal-Arch is a simplistic distributional model based on building type, floor area, energy-use and location. It was designed as an initial 'simple tool' to provide a public view into the California Commercial End-Use Survey (CEUS) data (described below). The tool's design simplicity is a result of the limited data available from the Cal-Arch CEUS. However, it is easy to use and provides a *relative* ranking of a building's EUI within the EUI distribution for the CEUS buildings' dataset.

The underlying data for the 'ranking' of the buildings is based on the California Commercial End-Use Survey (CEUS) which involves on-site surveys of a representative sample (2,800 sites) of commercial establishments throughout the state. Data are collected relating to building characteristics; equipment operation; and energy consumption. It will primarily be used to support the design and planning of energy efficiency programs and the Californian Energy Commission's demand forecasts. These data will be used to develop a detailed building characteristics database and electric and gas energy-use models. A statistical analysis of the database will be undertaken to estimate building and equipment characteristics including fuel shares, and end use saturations.

Benchmarking is the most popular method of assessing energy-use performance for a building. Unfortunately, the technique has three crucial disadvantages:

- 1) In order for benchmarking to be meaningful, it is necessary to compare 'like' with 'like'. However, even within national borders, different construction techniques, operation strategies and design solutions make it very difficult to assess the building. As a result, the population of buildings employed for comparison may be too small.
- 2) If the set of buildings are all underperforming, it gives an 'unintelligent' rating (or hierarchical ranking) to the building.
- 3) The energy saving potential is not scrutinised and too many simplifying parameters are made.



1.5.4 Green Building Tool (GBTool)

The Green Building Tool (GBTool) is a building environmental assessment tool developed by the Green Building Challenge (GBC 2005). International collaborations facilitating case study buildings have contributed to development of this tool which aims to develop a wide-ranging framework for sustainability assessment (Cole 2001). The GBTool research process involves global teams that determine adequate selection of performance indicators for buildings. These ‘green’ indicators include energy, materials, air quality, etc. The metrics are then analysed with an in-house building software program. Finally, participating countries selectively draw ideas to either incorporate into or modify their own tools.

An important objective of GBTool is its aim to “reflect the very different priorities, technologies, building traditions and even cultural values that exist in various regions and countries” (Cole 2002). The tool is not for direct application in society, instead, it is meant to act as a launch pad for development of new forms of assessment tools. The key issues include resource consumption, loading, indoor environment, quality of service, economics and pre-operations management. This sustainability tool is composed of twelve sustainability indicators, six of which are concerned with energy conservation issues. This highlights the important role of energy-use in sustainability assessment. However, this tool is not a BLC approach and cannot be seamlessly fitted into the project’s iterative phases.

This international effort highlights a framework and approach for any new assessment tool. The ability to set a benchmark and customise the tool to assess the building is a key benefit. Additionally, it highlights the importance of having an application related to the geographic location and building-use underpinned by a parent framework.

1.5.5 Building Management Systems (BMS)

Poor management of the internal environment leads to occupant discomfort; increased building energy consumption; and increased wear on process elements (Salsbury and Diamond 2001). Effective monitoring and controlling HVAC systems help mitigate energy-use for a facility without compromising the internal environment (Canbay et al. 2004). In the past quarter of a century, design solutions for HVAC systems within



buildings have moved towards the use of digital computers. Typically a Building Management System (BMS) utilises digital control to monitor or automate building services and security within a facility (Grimm and Rosaler 1997; Langston and Lauge-Kristensen 2002). Direct personal computer terminals monitor and operate units of the building through direct digital control.

Digital control facilitates more flexible and precise management for a facility allowing significant energy savings. Temperature setback; automated lighting and shading; and additional operations tied to energy-use can all be automated for maximum control. Facility Managers (FM) can better understand buildings through appropriate interfacing with the BMS and examining building sensors and controls process variables. This allows the FM community to appreciate how these components (and their inherent strategies) affect energy performance.

The latest BMS technology facilitates communication on the WWW via the general IT infrastructure within the building. This kind of technology facilitates the supervision of multiple buildings. Design teams can directly interface with the performance of their solutions from the comfort of their own headquarters. These systems are based on a Personal Computer (PC) running a web browser, communicating via a data network using Transmission Control Protocol (TCP) / Internet Protocol (IP) data transportation protocol to field-mounted controllers and sensors. Web-based browsers have many inherent advantages which include:

- 1) user friendly operating system with multiple entry points;
- 2) low operating costs; and
- 3) utilisation of an existing IT network (which leads to benefits and savings).

The cost implications of effective BMS systems are largely neutralised by the reduction in operational costs for a building. However, despite the potential for analysing performance history, BMS systems are rarely incorporated into frameworks to reduce energy consumption by the building (Hitchcock et al. 1998). The practice of fixing set-points is often considered to be ‘applying a BMS’ to obtain an energy efficient facility. However, BMS systems have far more useful beneficial capabilities as discussed above. It is this key advantage that is explored for use by the proposed methodology.



1.5.6 Performance Metric Tracking

Performance metric tracking is a performance-based life-cycle approach to the building energy assessment. The technique offers meaningful comparison of building performance with other dissimilar buildings (Karola et al. 2002). Performance metrics themselves are defined as quantitative criteria laid out in a structured format providing value across the entire BLC. They serve to define more clearly and quantitatively the performance objectives set out for the building. Utilising standardised performance metrics, a clear and concise manner of depicting a wide set of performance objectives may be retrieved which facilitate analysing the success of HVAC design decisions along with the performance of the building.

In order to engage in performance metric tracking, certain performance indicators must be calculated at various phases of the project. Performance indicators must be capable of prediction or measurement during project phases to evaluate the achievement of objectives. During the pre-design planning stage of the BLC, quantitative performance objectives are identified along with initial generic quantitative performance metric benchmarks. Once the BLC evolves into the design stage, these performance metrics are elaborated and evolved describing the performance of the building in far more detail. The performance of design solutions are evaluated and documented along with as-designed performance metric benchmarks. During the commissioning phase, the ‘as-constructed’ building performance is evaluated and documented as benchmarks. Finally, during the operations and maintenance phase, the building performance is continuously evaluated utilising BMS systems to their full potential (Section 1.4.5).

Tools such as Metracker (Hitchcock 2002) were developed for performance metric tracking. Performance metric tracking has several beneficial qualities:

- 1) It discards qualitative building energy performance aspirations which tend to be text-based and are liable to become lost as a building project moves through its iterative BLC phases.
- 2) It offers a set of *up-to-date* data that may be tracked to document the buildings performance meticulously.



- 3) It provides assurances for assessment of building energy performance in a myriad of disparate projects throughout their lifecycle.

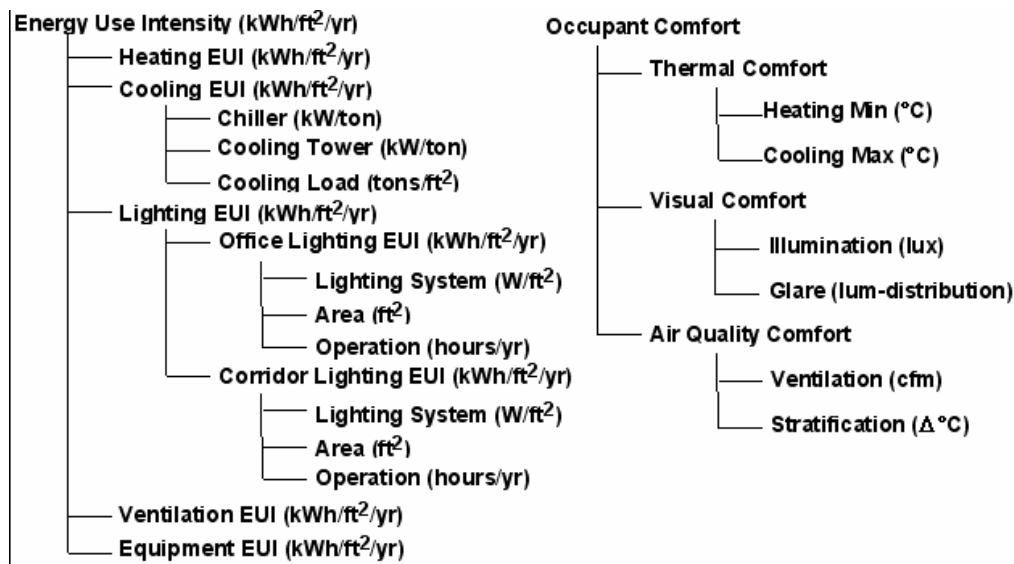


Figure 1-2 – Example of hierarchies of energy and comfort metrics (courtesy Rob Hitchcock)

While performance metric tracking has much inherent strength, it can be extremely difficult to compare buildings of similar type if they are located in dissimilar locations. Buildings located in different regions are subject to contrasting weather conditions and are influenced by unrelated building codes and regulations. These parameters may adversely handicap buildings and this disadvantage coupled with disparate local facilities management, construction practices, etc. lead to an inability to compare/contrast buildings.

Another important consideration is visualisation of the units for performance metrics themselves. The values of these metrics are difficult to conceptualise for non-specialised persons. Building energy-use quantification units such as EUI, cfm, kW/ton are incomprehensible for most persons involved in any building project.

1.5.7 CIB Performance Based Building

The International Council for Research and Innovation in Building and Construction (CIB) (CIB 1953) (formally Conseil International du Baitment) is a global networking organisation. They provide a cross-disciplinary platform for collaboration to improve the



built environment. The objectives of the association are to stimulate and facilitate international co-operation and information exchange between governmental research institutes in the building and construction sector, with an emphasis on those institutes engaged in technical fields of research.

In recent years CIB has identified performance-based assessment of buildings as one of its key areas of focus. CIB TG37 is task group set up in 1999 to assess the many issues and questions surrounding performance-based building regulatory systems and building models. They work to gather information and experiences related to these issues and questions. Several of these issues include:

- 1) the form of acceptable solutions;
- 2) the minimum level of performance;
- 3) the relationship of the acceptable solutions to performance-based requirements;
and
- 4) the issues surrounding documentation and publication of acceptable solutions
(Bergeron and Bowen 2001).

The CIB board has recommended that a program be established for preparing a compendium of validated models of performance. This online database would facilitate the use of the performance approach in building and construction. These performance models could utilise computational procedures and computer programs for building design or code adherence (Foliente and Becker 2001).

1.5.8 Building Energy Prediction

The energy performance of a building depends on numerous heterogeneous building and environmental features. Accordingly, predicting building energy performance is a multifaceted undertaking which grows exponentially with the magnitude and complexity of a building. During the design phase, it is not possible to experiment with the building itself in order to predict the performance of environmental design. The use of building simulation energy prediction software can significantly increase downstream building energy performance, reduce the amount of errors in design, increase the efficiency of



mechanical systems and decrease the time required to predict performance (Gordon 1969).

Prototype models are generated and considered as substitutes for the real building's systems. They are also simplifications of the system which are necessary to reduce input and computation time. The model is really a body of information about the system gathered for the purpose of studying the system. No unique model of the building will suffice as different models may be produced by different analysts who are interested in different aspects of the building or by the same analyst as their understanding of the building changes.

There are two different types of models which may be generated. The following two subsections discuss their pertinent details.

1.5.8.1 Static Mathematical Models

Static models of the building define the relationships between the building attributes (load schedules, number of people, wall type, etc.) under design conditions (extreme climatic conditions) when the system may be considered to be in equilibrium. This point of equilibrium may be changed by altering an attribute's value and therefore, the model enables new values for all attributes to be derived. However it does not show the way in which the new values were changed.

These models often incorporate massive spreadsheet calculations incorporating hidden macros and equations requiring input from several other spreadsheets. As a result, they tend to act as 'black box' units, making it difficult to leverage documentation of design for ease of referral and in no way communicate the design philosophy or design subtleties behind environmental design. These modellers cannot retain or consider the consequences of dynamic changes in a building. Ultimately, this traditional means of calculating design loads is an inadequate driver for an energy efficient building stock (Rousseau and Mathews 2003).

1.5.8.2 Dynamic Mathematic Models: Whole-Building Energy Simulation Tools

Before defining a simulation tool, it is important to understand what is being 'simulated'. A building is – in essence – a system whereby it is an aggregation of objects joined



together by some interaction or interdependence. Definition of the system should be broad enough to include the static entities but the principle interest is the dynamic subsystems and their interactions causing change over time. The information available to the simulation is proportional to the depth and resolution of the model. It is this difference in resolution which generates the difference between the ‘real world’ and the ‘simulation model’. It is in its very nature for the simulation model to strive to simplify the characteristics of the real world by simplifying the input.

There are two classes of simulation models for building energy simulation:

- 1) The first is uniform time increment models. This is the most popular form of modeller. These modellers are used where changes are smooth (e.g. the movement of an aircraft, thermal environment in a building, etc.).
- 2) The second class is event driven simulation modellers. These models are less common due to their complexity but they offer the possibility to leverage more accurate information. They are used where changes are predominately discontinuous (e.g. the order and manufacturing processes in a factory).

Both forms of system modellers are discussed in Geoffrey Gordon’s book titled “System Simulation” (Gordon 1969), however this dissertation focuses on the popular uniform time increment simulation modellers which dominate the building energy-use marketplace.

Uniform time increment simulation modellers of this type derive the change in building attributes as a function of time. These modellers are used as the predominant activities cause a smooth change in the attributes of the building. When buildings are being modelled mathematically, variables are controlled by continuous functions (linear algebraic equations) which describe the rates of change. As a result, the software behind the modellers consists of many levels of differential equations.

Input data to simulation models are structured and ordered and events - pertinent to building performance - may be managed dynamically in event schedulers and results derived through analytical solutions. Another significant advantage is their flexibility. These modellers can simulate synchronous and asynchronous events (e.g. shifts in weather patterns, alteration of building use and contrasting seasonal control systems) with



arbitrary timing delays. Dynamic alterations to tangible building components (including shading devices, window size, wall changes, boiler selection, etc.) are possible and are all analysed on an equal basis. Algorithms and equations – evolved and matured over time – are programmed into simulation engine so that the interactions between physical and dynamic properties of tangible objects (wall, HVAC system, etc.) and intangible objects (load schedules, Energy Conservation Measures (ECMs), etc.) can be calculated.

Despite these many benefits, whole building energy simulation modelling has not been widely adopted by the design community. The problem with simulation software is that the user is forced to fragment the design process which makes it very time-consuming to keep up with client's and AEC community's building alterations during the design process. The time required preparing vast amounts of input information and process the output is an objectionable project overhead. Even experienced users in the field of simulation modelling require significant time in preparing objective energy models. This significant issue is compounded by low market interest and the high time-cost of energy performance prediction. These difficulties make it difficult to leverage the potentials offered from these building simulation tools (Mourshed et al. 2003).

Change of design is an integral part of the design process and a whole-building simulation tool which integrates seamlessly into any design process is desperately needed. However it is important to note that energy performance assessment is not the only process in the building industry, many other processes such as acoustic assessment, fire safety analysis, structural analysis, etc. could all benefit from a closer integration. As a result, an 'open' environment would provide the solution whereby design stakeholders in the project could employ specific views of one central description of the building for their own purposes. Such an environment is discussed in Section 2.3.5.

It is also vital that the simulation software would need to be an 'open' system so that third party vendors could incorporate their products 'software add-ons' into the main software and users could benefit from employing their expertise. Such a simulation tool is discussed in Section 4.4.

1.5.9 Summary of Building Performance Frameworks

Operational building energy-use is a *key issue* for the sustainability of buildings in society. Many of the existing and widely used sustainability assessment toolkits offer



‘life cycle’ appraisal of a building. However, with the exception of Performance Metric tracking, these frameworks have a limited impact as they offer limited assessment of energy-use management during the operations phases of the BLC.

Given the current economic environment driving government agencies’ desire to mitigate demand on global energy production by the building stock, the absence of an operational assessment of the facility is a significant adverse issue which highlights a void within the marketplace.

1.6 Preface to the Following Chapters

Chapter 2 discusses the key issues involved in undertaking life-cycle assessment of building energy-use. It discusses the ‘why’ in greater detail and presents the ‘how’ as an introduction to Chapter 3. Chapter 3 discusses the assessment method toolkit in detail. Chapter 4 presents the tools required for the methodology. Chapter 5 discusses a trial implementation of the methodology leaving the Chapter 6 to discuss the findings and overall conclusions, recommendations and future work drawn from the research.







Chapter 2

Hypothesis

Chapter 2 discusses the key faults within the industry which are currently hampering a more performance-based approach to building design and assessment. Additionally, it introduces many of concepts and data warehouses employed in order to assess, quantify and convey the energy performance of a building using the proposed methodology.

“Pencils have erasers because people make mistakes.”

-Ty Ross



2.1 Introduction

As humans, we reside within the confines of the built environment for most of our lives. Due to our physiological and psychological needs, we require adequate levels of fresh air and thermal comfort from this built environment. Many heterogeneous agents have a bearing on the thermal comfort provided by a building. For example, the advent of computers and other office equipment, heavily glazed facades, poor shading, deep floor plans etc. have increased cooling loads within buildings. This has called for more proficient design and operation frameworks capable of responding to dynamic shifts and requirements from the internal environment.

As discussed in the previous chapter, we, as human beings, are ‘energy junkies’: we tend to ignore inflated levels of energy-use unless we are directly penalised. But the sustainability of society’s energy requirements is becoming an increasing concern. New building legislation (Section 1.4) is encouraging a more sustainable building stock. A well performing building is one that should “support high levels of energy efficiency, occupant comfort and productivity, and indoor air quality, with low operating and maintenance costs” (Hitchcock et al. 1998).

Unfortunately, defining and appraising a building’s energy performance is often perceived to be a nebulous and confusing task. The dynamic process of ‘energy-use by a building’ is affected by many disparate agents that are often difficult to measure and predict. These agents include the external conditions, internal conditions, internal occupancy load profiles, changes in building use, deterioration of the building envelope, etc. It is this perception that often leads to an insufficient evaluation of a building’s performance over its entire lifecycle.

This research considers ‘increased communication’ to be the key to solving the aforementioned problems. This calls for increased exchange of information between:

- 1) persons and teams engaged in the project (e.g. architect, engineers, contractors, client, occupants etc.);
- 2) software tools (CAD tools, HVAC design aids, fire safety analysis tools, structural analysis tools, etc.); and



- 3) disparate project teams (analysis of a projects successes and failures feeding forward into the next design).

The building process is well documented as being a fragmented industry littered with events of poor communication between project participants and especially poor communication throughout the iterative project phases (O'Sullivan et al. 2004). This research finds that more efforts are focussed on specific stages of the BLC and *not* the overall picture that should support all project stakeholders. Upstream design 'intent' and downstream operational 'experience' are not necessarily comparable. The solutions offered by structural engineers are allowed to work – buildings are generally not falling down – as they act in a proactive process. However, mechanical HVAC designs are *forced* to operate in the later stages ('reactive' stages) of the detailed design stages and as a result, design decisions are forced to be made in an *ad hoc* basic (Mourshed et al. 2003). This leads to facilities requiring too much energy and managing inadequate levels of thermal comfort.

Current industry practices are resulting in 'black box' additions to the building stock. An inability for all project stakeholders to appraise energy-use results in a building stock littered with energy-wasters and as such, there is no understanding as to the effects of designs and no feed-forward loop to augment a knowledge-base for the next design. A new building energy performance methodology tool is required providing an easily understandable language facilitating performance appraisal to all project stakeholders. This tool must communicate performance in an unbiased environment which quantifiably couples internal thermal comfort satisfaction with energy usage throughout the BLC. The pragmatic concerns of project participants (owners, designers, building managers, occupants, etc.) must be addressed and incorporated as part of the language in order to assure compatible design and operation.

2.2 Problem Statement

Sir Isaac Newton is famously quoted as saying,

“If I have seen a little further, it is by standing on the shoulders of giants.”



This quote would appear to be particularly apt for an industry that requires pools of expertise and knowledge to be brought together towards generating a high performance product. There is little benefit in assessing a building if the *consequences* of design decisions cannot be unambiguously quantified and tied to the holistic performance of the building (and ultimately, fed forward into the next addition to the building stock).

These famous words support the need for documentation of performance-based analysis throughout the BLC and developing a knowledge-base within the industry. Many errors in design are avoidable through the querying of case studies and augmenting the wealth of knowledge contained within (Petroski 1994). Without a clear *visualisation* of environmental design impact, no serviceable impact can be made on the future of society's building stock. The marketplace will be condemned to repeat a history of poor design, ineffective building operation, elevated CO₂ emissions and an inadequacy to emulate the success stories.

The following subsections discuss the details of five significant nuisances which remain unaddressed within the industry and are combining to leave the building stock heavily dependant on available energy reserves.

2.2.1 A Flawed Building Design Process

The roles taken by energy efficiency during the iterative building design process stages are complex ones. An energy efficient building may be solicited by the client during the project brief and tender stages. However the AEC community are rarely compensated for the extra effort required to evaluate the possibility of alternative designs in the pursuit of an *energy efficient* design. This problem is compounded by a lack in compensation for regular assessment of projected energy efficiency. A further problem is the traditional payroll structures that often financially penalise stakeholder teams who pursue load reduction that result in equipment downsizing which may result in a fee reduction (Hitchcock et al. 1998).

Historically, design and construction teams' efforts are tailored towards bundling sets of O&Ms and 'as-built' drawings with the handover of the building. These AEC teams are geared towards a huge effort for *practical completion* and very little *consultation or*



engagement post-occupancy. The root of the problem is the disparate ‘views’ taken by project stakeholders. Building owners view the information (O&Ms) from upstream design and construction process as a strategic asset; whereas contractors view it as a final deliverable for project close out. However, the end of the construction process is the *dawning* of an evolving business facility and it is not considered to be unusual for an effectively designed, built and handed-over facility to be systematically decommissioned by its operators due to poor management (Selkowitz et al. 1996). This is *not* due to any degree of incompetence on the part of the operators or building manager. The root cause is *inadequate communication* of design subtleties and a *lack of understanding* of the design philosophy (Piggott 2004). This is augmenting the operational costs for a building (Wilde et al. 2002).

This practice is analogous to handing a plane over to a pilot without any instruction on how to operate the myriad of controls in the skies. The training of building managers along with analysis of post occupancy building energy-use should be a basic requirement along with the availability of a strategy/methodology to further improve their own education about the building’s performance.

Additionally, this disconnect within the industry is lending itself to a practice where the repetition of history’s mistakes are commonplace. This is true of design and operational mistakes. Building designers rarely participate in post-occupancy performance evaluation for facilities which creates a situation whereby each building is a prototype and no ‘lessons’ are leveraged in order to refine and optimise solutions for the next design. As a result, no augmentation to knowledge in the pursuit of energy-efficient buildings is ever realised. Even ‘best practice’ commissioning does not usually include energy performance tests, which may require the evaluation of systems over lengths of time (Hitchcock et al. 1998). This legacy of repeating flawed building designs could be negated by adequate feedback loops in a BLC assessment toolkit. However, popular assessment methods employed within the industry are not archiving any performance of the building (at any stage of the building life cycle). They merely provide generic labels for facility design and do not highlight any potential areas of improvement for energy management. As a result, they do not provide value across the entire BLC (Hitchcock 2003).



Before the development of computers, a variety of tools were utilised during a building project's evolution. With the advent of the digital age, computers are capable of streamlining a myriad of processes. However, unlike the aeronautics and automobile industries, effective realisation of the potentials offered by IT in the building industry has yet to be realised (Best and Valence 1999). Proficient utilisation of *interoperable* environments (Section 2.3.5.2) can expedite work on industry process tasks, however a report published in the US estimates \$15.8 billion per year is *lost* in US capitals industry due to inadequate use of interoperability in the workplace (Gallaher et al. 2004). The study, conducted in the year 2002, adds that this figure is likely to be a *conservative* estimate. Additional factors accounted in the report include the highly fragmented nature of the industry, the continuation of paper-based design practices and inconsistent technology adoption by the AEC&FM community. The defining conclusion points out that the building industry must adopt *technology* more whole-heartedly.

2.2.2 Environmental Design Aids

Achieving energy efficiency costs money. However, the additional cost of environmental design and management aids is recoverable out of the savings in ongoing costs. Unfortunately, legacies of poor design and operation process create barriers which block their adoption:

- 1) There are no incentives for project teams to adopt these tools unless they are specified in the project specification. This is because the market is flooded with short-sighted practices guided by 'lowest price'.
- 2) The design team does not have to pay for running costs for the building and has no incentive to explore energy saving technologies.
- 3) The clients of these facilities are not educated enough to realise that their power bills are significantly over-inflated and major savings are achievable (Section 2.2.4).

There are a plethora of environmental design aids in the marketplace that consider the domains of thermal, visual and acoustic effects on human comfort (examples include



ESP-r (ESP-r 2006), BDA (Papamichael et al. 1997), etc.). Unfortunately, development activities on building simulation modelling have done little to integrate with the design process stages for which they have been intended as they require a more integrated approach from the entire project team. Even with the addition of user-friendly graphical interfaces, the adoption of these simulation packages has been limited to a small number of specialised consultants and *not* the wider building project team. It is essential that adoption of these tools is addressed in order to realise the “tremendous benefits of informed decisions that these programs can support” (Papamichael et al. 1997).

Unfortunately, the only design aid tools which appear to be making inroads into the industry are tools like IES (IES 2006). The disadvantage of these tools is that they are merely expediting the flawed processes mentioned in Section 2.2.1. Due to the small amount of time given over to environmental design, a simplified tool such as IES is extremely tempting for design teams who wish to pay lip-service to ‘full BLC analysis design practices’. As a result, the industry will never see the potential benefits offered by a suite of integrated tools with their inherent specialities and domains. Instead, the ‘building design aid’ industry will be dominated by vendors offering proprietary environments and ‘black-box’ answers to BLC analysis.

2.2.3 Buildings’ Intrinsic Energy Saving Potential

The key goal for any *sustainable* building is a safe and secure operational energy requirement (Mahling and Lehman 2005). Experienced building energy professionals appreciate that buildings are not achieving their intrinsic energy saving potential. Saving of 10%, or *significantly* more, are possible utilising effective housekeeping measures and monitoring routines within existing buildings (Dix 2003). It is imperative to note that a low energy design does not imply that the building manager will preside over a low energy building (Selkowitz et al. 1996). An efficient HVAC plant for a facility is seen as the most cost-effective option to achieve and improve the energy efficiency of a building (Canbay et al. 2004). Much can, and must, be done to maximise energy efficiency. Examples schemes include:

- 1) educating the building manager and the occupants;



- 2) optimising energy-use control strategies;
- 3) effectively informing maintenance and operation staff about the building's energy saving potential;
- 4) regularly monitoring and reviewing building energy-use performance;
- 5) identifying poorly set up control systems;
- 6) efficient logging of building operation to minimise time wasted assessing ineffective strategies and maximise the amount of the time the building is running efficiently.

Achieving the intrinsic energy saving potential of a facility is not the sole responsibility of the operations staff. In order for these project individuals to operate a building successfully, an adequate communication of design philosophy by design teams is required. Unfortunately, crucial assumptions made during design stages are poorly recorded and often not broadcast to pertinent teams responsible for the running of a building. A review, carried out by a large insurance agency for architects and engineers, cited poor communication of design philosophy as a common reason responsible for HVAC related liability claims (Thompson 1997).

The key to this problem is *increased communication* by the environmental design team post-occupancy. Unlike the static product offered by the architect/structural engineer/etc. the product offered by the environmental design is a dynamic entity affected by many heterogeneous agents. It is vital that the environmental design team remain engaged in the project in a consultative role in order to remove the possibility of the client/building manager decommissioning the building due to poor operations practices.

2.2.4 Including the Client

Virtually every decision made over the course of a project has long and short term consequences. Many of these consequences are immediately visible (such as window selection, etc.). However the interdependence of many heterogeneous decisions has inherently more subtle environmental consequences. These adverse environmental penalties – imposed due to inadequate design – are difficult to visualise during the design and construction phases of a project. It is important to note that these issues do not



manifest themselves on the drawings in the design office; they are only experienced as the BLC enters its operational phase. However, consideration of these issues has almost no direct input to the building, planning, design and construction process. It is widely appreciated that when the consequences of design decisions tend to be more abstract, they receive little extra attention, resources or fine-tuning (Selkowitz et al. 1996). However these ‘abstract’ issues (for the design team) grow to be tangible overheads (for the client) as the energy bills arrive. It is imperative that the client becomes educated in order to change an outdated and ineffective design process.

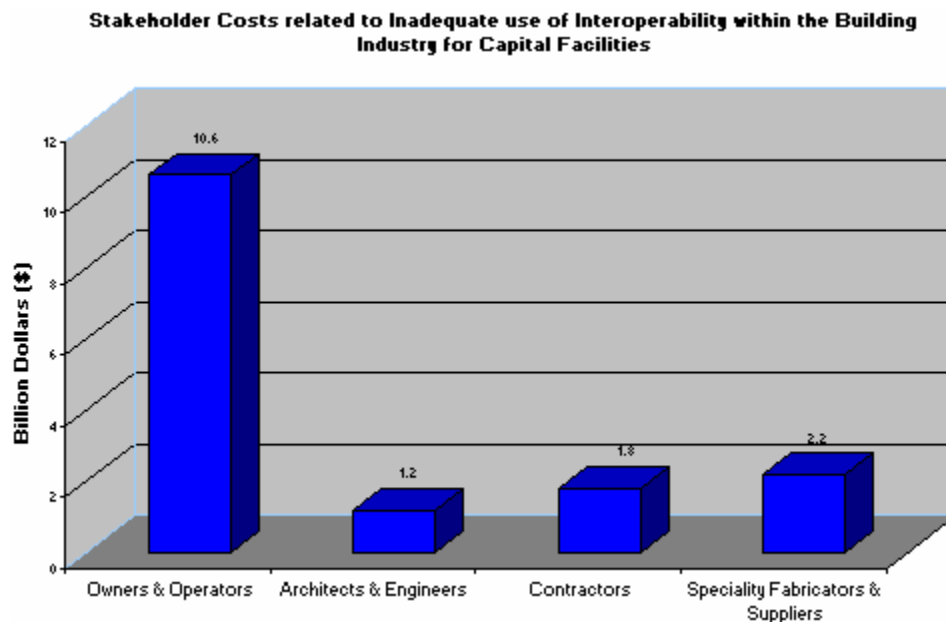


Figure 2-1 – Stakeholder costs related to inadequate use of Interoperability within the building industry for capital facilities (courtesy Gallaher et al., 2004)

Building owners are at the very core of the industry and ultimately, it is the proprietor of the facility that incurs the life-cycle costs. In 2004, the National Institute of Standards and Technology (NIST) commissioned a study (first mentioned in Section 2.2.1) to identify and estimate the efficiency losses in the U.S. capital facilities industry resulting from inadequate interoperability among the AEC&FM community. The final report of this study estimates the cost to be \$15.8 billion per year (Gallaher et al. 2004). The details of interoperable environments are discussed in more detail in Section 2.3.5, but the breakdown by stakeholder groups finds building owners and operators shouldering $\frac{2}{3}$ rd



of this expense (\$10.6 billion) due to excessive and ineffective design, operations and maintenance. It is logical that ineffective upstream practices will add to downstream costs (Figure 2-1). However, the significant matter here is that an educated client *can* change the building process. To coin a phrase, “he who has the gold, makes the rules.” Owners have the power to coerce a higher performing and deeply collaborative approach from the AEC&FM community.

In order to mitigate inflated operational expenses, clients must change their perspective and realise they can act as drivers for the process that *would* deliver a higher performing product. It is time for building owners to become more fully engaged and begin driving a *life cycle* approach within the industry. Building owners have little interest in additional annual overheads payable to government agencies. With the impending liability of owning an inefficient building, the legislation proposed by government bodies (Section 1.3) empowers the client to insist on more energy conscious design solutions. However, clients generally have no experience in what a ‘green’ solution actually entails. This liability is compounded by the absence of having a language to communicate to supervise more energy conscious approaches.

This is significant as it highlights the fact that an assessment scheme incorporating a language of communication for specific design decisions that is applicable to both professionals and non-professionals alike is of high market interest. Any new assessment scheme should be oriented towards the manner in which investors make decisions. This will ensure that the client’s requirements are constantly and consistently being addressed throughout the BLC.

This research points towards increased education of the decision makers in *public bodies/institutions* which would significantly steer the design process towards more sustainable practices due to the large numbers of buildings procured and operated every year by these agencies. It is envisaged that if these building owners take the initiative, the general populace would follow suit. However, with the advent of the EPBD (Section 1.4.1), it will become clear who is acting responsibly and who isn’t. This research aims to provide the client with a tool to drive a more *integrated* approach in order to effectively and efficiently communicate with project teams in order to manage buildings in terms of energy-use and CO₂ production.



2.2.5 Productivity and Indoor Environment – The Ergonomics Link

Research points out that more recognition must be given to the fact that buildings add value to an organisation's core business (Williams 2000). A person's workplace is like a second home, he/she occupies their work environments for 8-12 hours during any working day. However, key factors such as temperature and humidity can cause physical discomfort. This is significant given the increasing discussion on the 'life cost ratio' which is generally described to be 1:10:200. This means that on average, the approximate cost of running a building is ten times higher than the capital cost, but the cost of paying salaries is far greater still (Clements-Croome 2004).

Several surveys have highlighted crowded work spaces, job dissatisfaction and the physical environment as the main factors affecting productivity (Carnevale 1992; Clements-Croome 1997). A report submitted to the Royal Academy of Engineers in the UK points to the cost of ownership and maintenance of a building is typically about 3% of the overall personnel costs (Evans et al. 1998). The report goes on to estimate productivity improvements by as much as 17% are possible given properly designed and managed facilities.

Absenteeism in the workplace costs the UK economy £12 billion every year and a significant portion of absenteeism can be accounted for by poor work environment (Clements-Croome 2003). Employee states of lethargy are prevalent in buildings exhibiting 'Sick Buildings Syndrome', greatly reduces the quality mission of companies (Clements-Croome 2000; Pang 2003). Accordingly, it is desirable for business to offer and maintain healthy work environments to mitigate financial losses. An additional adverse penalty is that unhealthy and poorly maintained work spaces create an atmosphere whereby employees feel uncared-for by their employers. Research highlights as much as 16% of productivity is directly related to job satisfaction (Williams 2000).

There seems qualitative acceptance that the built environment has impacts on both personal and community health. Ergonomics is defined as the applied science of equipment design, as for the workplace, to maximize productivity by reducing operator fatigue and discomfort. Ergonomics can clearly be seen to play an important role in the design of buildings, however, historically, it has received little attention (Best and



Valence 1999). The more attention paid to ergonomics during the early stages of design, the less changes will have to be made to the facility in order to attain acceptable comfortable conditions within the building (Karwowski and Marras 1998).

Small increases in productivity of 0.1% to 2% can have dramatic effects on the profitability of a company (Clements-Croome 2003). In the search for more productive work place, it can be clearly seen that facility managers and the operations personnel of a building play a critical role and it is imperative that adequate feedback is given to the design team in order to affect future projects (Evans et al. 1998).

2.3 Proposal for a New Systematic Performance-Based Assessment

This research proposes a voluntary assessment scheme requiring an integrated approach that highlights vital energy performance and efficiency issues. It accommodates all the requirements of the engineer, architect and the client offering environmental ‘building design and operation information’ in a timely and cost-effective manner. The toolkit, discussed in detail in Chapter 3, is referred to as the BECs (Building Effectiveness Communication ratios) methodology. The remainder of this chapter presents the foundation stones of the methodology and several tools, technologies and environments that *underpin* BECs.

Within the building industry, a myth has developed that there is a correlation between beauty and sustainability. It seems appropriate to return to the analogy of buying and owning a car. Not too many potential car owners buy a car without querying the engine size and the expected miles per gallon. Why? Because not too many potential car owners can afford a 3.2 litre engine given the expensive, and currently rising, prices of fuel (energy). The significant issue here is that the *client* has an indicator for *discriminating* between an energy ‘efficient’ vehicle and an energy ‘intensive’ vehicle. In essence, the energy ‘guzzler’ becomes an unattractive and unsolicited asset for the client. BECs’ aim is to provide a similar means of discrimination within the building marketplace and depict energy intensive facilities as unattractive options for the client.

BECs values are a form of energy performance measurement and the methodology systematically monitors the building (and its associated components) against binding



targets in order to maintain a standard drive towards further improvement of energy performance throughout the BLC. Acting as a driver for intelligent building design and operation, it assesses the impact building operation will have on available energy supplies. A conscious effort was made to build on the strengths of existing tools and methods, most notably, performance metric tracking (Section 1.5.6). However, while measured HVAC time-series *are* descriptive of building performance, they are wholly dependent on strict boundary conditions (weather, control strategies etc.). It is impossible to assess the many disparate impacts of these heterogeneous factors in a single output without any comparison with an ‘ideal’. Whole building simulation models (Section 1.5.8.2) offer a solution. Pertinent building energy-use performance indicators are developed and benchmarks for charting building energy effectiveness are integrated into predefined ratios. Utilising an archive of performance indicators stored in a single Building Information Model (BIM), the proposed assessment method renders a portrayal of easily understandable performance indicators for energy performance assessment. The specifics of this technique will be explored in later Sections.

The strength of the proposed methodology is its simplicity. Each person (including the building owner) involved in the project may comprehend the message of these data in a timely and cost effective manner. Specific components within the building – that have an impact on energy-use – are linked to these performance indicators (ratio values) to track their performance over time. With these indicators in toe, it is possible to document the rationale and impact of design decisions over the entire BLC (Figure 2-2).

These performance indicators are not just for the design team, they are also useful for facility managers who can reference these performance specifications to *realise* the potential energy efficiency of the building. This is a new and essential form of Enterprise Energy Management Systems (EEMS) that can integrate the graphical and database systems for more effective decision making throughout the BLC (Mahling and Lehman 2005).



Figure 2-2 – A new assessment toolkit for application across every stage of the BLC to support a better product and influence future design

Vast quantities of data are required for adequate assessment of building energy-use. These data are elicited from various tools (e.g. building energy prediction simulation engines, energy monitoring systems, etc.) and translation into *useable* and universally appreciable information is vital. The following subsections detail the issues raised when utilising such a toolkit for driving energy efficiency forward in the building industry.

2.3.1 Systematic Methodology

A standard systematic methodology for visualisation of performance data over the entire BLC provides immediate understanding regarding the impact of design decisions and management strategies. Vital design and operations information is catalogued, stimulating motivation for building process participants to alter their current outdated practices of design and operation (Section 1.3).

A simple example of utilising BECs could be to scrutinise a cooling coil located within a specific Air Handling Unit (AHU) mechanical system. Selection of a cooling coil involves investigation of sizing parameters, on-coil and off-coil conditions and many additional parameters. During the design stage, by associating a performance indicator with this component, a documentation of the rationale behind the design decision is made. This documentation can be referenced as the BLC evolves to scrutinise the effectiveness of the cooling coil. This also helps to promote an energy efficient solution for the building from the outset. The pragmatic approach required at each phase of the BLC is outlined in Figure 2-3.

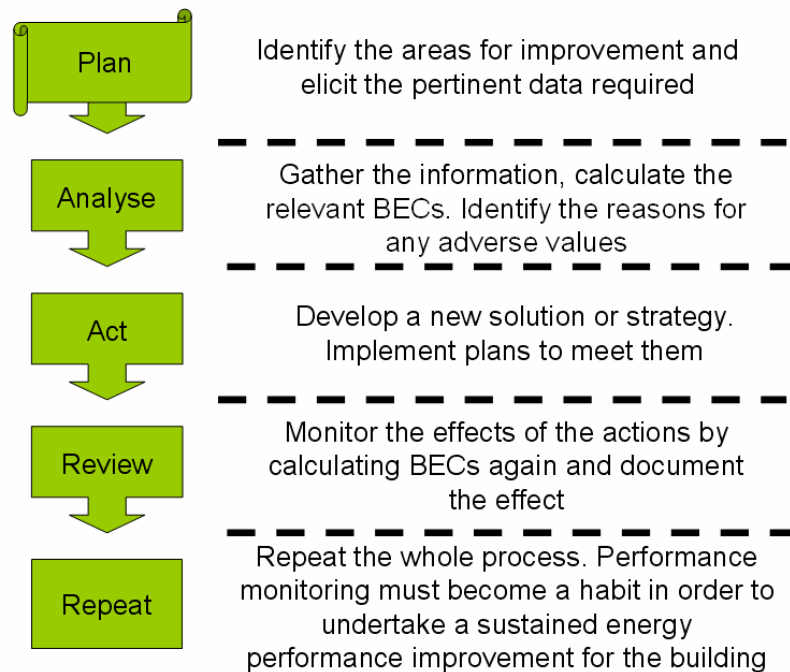


Figure 2-3 – Systematic approach required by the BECs methodology for insurance of high levels of energy performance

2.3.2 Expected versus Actual

The goal of BECs values, for a given design solution under assessment, is to display as a quantitative measure what is achieved versus what is expected. It acts as an easily understood ratio with values ranging from zero to one (Figure 2-4). As can be seen from Figure 2-4, calculating BECs involves quantifying a numerator and a denominator. The numerator represents the ideal level of energy consumption for the solution under scrutiny. The denominator represents the actual level of energy consumption. However the numerator and denominator may change as the building move through its life cycle. The sources for the numerator and denominators are explored in subsequent sections.

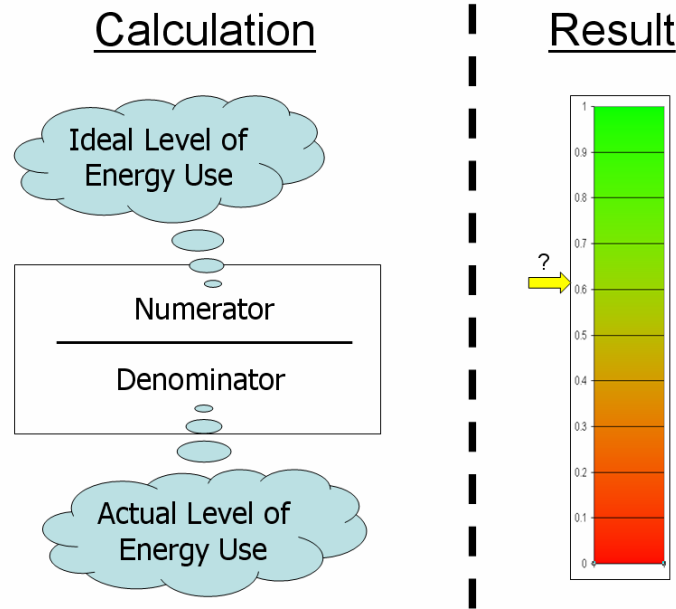


Figure 2-4 – Calculating and displaying BECs values

2.3.3 Data Warehouse

Analysis of overall energy-use (utility bills, etc.) is insufficient for building performance evaluation (Hitchcock et al. 1998). Employing tools and technologies that facilitate the appraisal of the many disparate systems within the building moderating effective operation is vital in order to adequately evaluate and qualify the performance of the building. This involves employing (1) a BMS system (Section 1.5.5) for archiving performance history and (2) a whole building simulation package (Section 1.5.8.2) for performance prediction and specification of a benchmark level of performance.

Quantitative targets (performance metrics) introduce a form of *assurance* for project participants. It is essential that ‘someone’ or ‘some team’ is *responsible* for energy efficiency in a building. All too often, it is ‘someone else’s fault’. BECs values, described in the subsequent subsections, depict important information for the design team which include clear and measurable targets. This is vital as it finally coerces participant *responsibility* within the project team to meet the ergonomic needs of the client and the low-carbon emissions targets – associated with energy efficiency – required by society. Certain members of the project team (including the client) are responsible for achieving



or stipulating these targets and they can all be integrated into the design, construction and operation processes.

2.3.3.1 Building Management System

A wise saying, which is one of the guiding principles for the development of the methodology, points out that:

“If you can’t measure it, you can’t manage it”

For the last 20 years or so, the ability of a BMS (Section 1.5.5) to highlight poorly performing energy performance in a building has been with us, however this medium is rarely if ever used in this manner (Dix 2003). Many of these BMS systems use a data communication protocol referred to as BACnet (Building Automation and Control NETWORKS) technology.

The proposed assessment methodology makes use of this medium by eliciting pertinent data from this digital building control medium. It does so by receiving energy-use information from sensors located within the building which provides a ‘view’ into the building’s actual energy performance.

Historically, building sensors located within the building are not properly maintained. However, as outlined in Section 1.4.1, regular commissioning and maintenance will become a priority for building owners due to impending legislation. This is significant, as it will delineate the actual energy-use of the building. It is this vital data which many within the services industry believe will play a significant role in aiding compliance with the proposed EU legislation (Section 1.4.1) and it is the linchpin for BECs energy-use assessment.

2.3.3.1.1 Actual Performance Metric

It is not sufficient to track whole building energy-use through utility tariffs etc, a higher resolution of energy-use is required in order to understand the intricacies of the building’s performance. As described in the preceding section, the actual energy utilised to manage the internal environment for the building can be extrapolated from the sensor readings



stored in the BMS's archiving facility. The *level* of sensing within the building dictates the *level* of analysis possible by the proposed BECs framework. It facilitates teams to assess where problems *may* lie. For example, if an AHU contains adequate sensing of temperature and humidity at relevant points, it becomes possible to assess the effectiveness of individual components within the AHU and optimise the efficiency of the plant. Possible values describing energy consumption may be interpolated from temperature, humidity, meter readings and other discriminating BMS values.

2.3.3.2 Simulation Tool

Simulation today is mainly undertaken during the design stage of a building as a form of design checker (Section 1.5.8.2) or during the retrofitting stages of a building. However, energy simulation provides an excellent tool for building life cycle energy efficiency management. Proficient utilisation of energy simulation and energy performance assessment throughout the BLC offers the ideal opportunity to improve the energy performance of the entire building stock.

A major prerequisite in aiding decision-making for the BECs methodology is the ability to *predict* performance. Whole-building energy simulation programs are excellent tools for assessing and mitigating energy-use in buildings. These tools facilitate precise and timely assessment for the adoption of strategies and technologies to improve building energy efficiency. These increases in energy savings coupled with maximum ROI (return on investment) and most importantly, thermal comfort, provide an excellent enabling medium for the industry.

The following two subsections discuss the two distinct views of the building employed by the methodology in the whole building simulation model.

2.3.3.2.1 Benchmark Metric

Without binding targets, it is impossible to move towards a sustainable society (Zimmermann et al. 2005). The following two subsections outline two different benchmark-metric models which may be employed to aid a systematic appraisal of building energy-use performance.



These models act as an *insurance of design* for the client. Values are solicited from a simulation model however the vital design boundary conditions are prepared in ‘round-table’ discussions with the entire project team and the client.

2.3.3.2.1.1 Benchmark Metric – Whole Building

In order to define a whole-building energy-use target for the design team, a suitable simulation model must be configured. This model contains information related to the building’s boundary conditions (these include: space-use, building form, location, etc.). However, the significant issue with this model is that it is *system-independent*. Accordingly, resultant values endeavour to define the minimum energy load required to facilitate a thermally comfortable space. The benchmark is computed based on efficient use of energy and as such, they provide a quantification of minimum building energy-use without imposing adverse penalties due to system selection or component deficiencies.

This involves a pragmatic approach by considering the distinct spaces within the building. In a similar fashion to the benchmark model, the spaces are broken down in terms of the number of people, their activity level, the hours of occupation, the light levels required for work and the amount of heat generated with the space. Additional effects for consideration include space infiltration and other issues that impact on the energy-use within the building. This does involve a degree of competence and experience from the modeller.

2.3.3.2.1.2 Benchmark Metric – HVAC System

Once a HVAC system has been selected during the detailed design phase, all components may be autosized¹ in the model configuration. As a result, the model employed for representing benchmark values is configured with a 100% efficient description of the HVAC system in the building. This will leverage the minimum level of energy-use required by an ideal version of the installed system. These values can be employed to assess the effectiveness of actual performance for individual components.

¹ This term is used to denote a software function available in many energy simulation tools which facilitates generation of the ‘best-case’ process variable (flow rate, etc.) for a particular unit in order to leverage maximum efficiency from the system.



2.3.3.2.2 *Simulated Metric*

The predicted energy-use is leveraged from a whole building simulation model. This simulation model offers a system-dependent prediction of energy-use for the building. However, it is important to understand the subtle differences between each successive model according to life cycle phase and the application of the data within the BECs framework.

2.3.3.2.2.1 Simulated Metric – Early Design Stage

A series of systems are configured in distinct models in order to aid the design team make more a more informed selection decision. These simulation models are an evolution of the ‘benchmark metric’. The files are configured with alternative HVAC systems. Process variables (such as air and water flow rates, etc.) are autosized at the early stage in the design phase. Accordingly, the configuration process is expedited in order to provide the design team with information in a timely and cost-effective manner. Each one of these models predicts the energy required to mechanically service the building in order to achieve adequate levels of thermal comfort.

2.3.3.2.2.2 Simulated Metric – Detailed Design Stage

Once a particular HVAC system has been selected, the model is developed. Previously autosized process variables in the simulation model are configured with information from catalogue data and updated schedules of operational intent. This development is carried out pragmatically throughout the detailed design stages in order to delineate a more accurate prediction of operational energy-use.

2.3.3.2.2.3 Simulated Metric – Commissioning Stage

These metrics are an *update* of the previous simulation metrics. During commissioning tests, flow rates, temperature profiles and many other discriminating factors are recorded. Accordingly, all process variables are updated in the system model. Any alterations to process variable setpoints are made in the model. This updated simulation model offers a ‘first pass’ at a calibrated model which mirrors the actual building’s performance.



Ultimately, values elicited at this stage of the life cycle offer a more realistic depiction of the minimum levels of energy-use required by the building due to its environmental design. It is the first form of ‘design feedback solution appraisal’.

2.3.3.2.2.4 Simulated Metric – Operation Stage Performance Target

These simulated metrics are leveraged from a fully calibrated system model. The model is calibrated from BMS data in order to ensure the model mirrors actual building performance. Accordingly, it should be noted that the accuracy of calibration is wholly dependant on the level of sensoring existing within the building.

The operational management of the actual building is mirrored in the simulation model. As a result, these ‘simulated metrics’ provide a binding performance target for operation for the facility management team (Section 3.2.2).

2.3.3.2.2.5 Simulated Metric – Operation Stage for System Optimisation

The calibrated simulation model outlined in the previous section becomes a launch-pad or test centre for operational strategies that can be employed to reduce energy consumption. This facilitates alterations to the control logic that is actually used in the building. Many disparate energy reduction schemes may be employed in the model in order to drive building operation towards its minimum energy saving potential.

2.3.4 Communicating the Information

There is no doubt that the availability of pertinent information to a project team lends itself to a more efficiently product. However this research has attempted to adopt a ‘*less-is-more*’ strategy when communicating pertinent building energy-use data. Research has highlighted that humans prefer ‘graphical charts’ rather than ‘tabulated text’, due to our perception system constantly seeking to find structure in order to comprehend an environment (Maguire 1985). While trying to communicate vital information, Tufte (1990) set out sets of guidelines;

- 1) Simple and clear is better;
- 2) Extra ink is bad;
- 3) Superfluous information detracts from the impact of graphics.



The guiding principle points out that depicting uninformative depth raises adverse penalties because it lends to misunderstandings and shadows the principle item of interest (Tufte 1990). BECs' graphs attempt to comply with these guidelines in order to communicate its energy-efficiency indicators of performance. As a result, BECs assessment method must be robust enough to display building performance over a variety of conditions but concise enough as to not *confuse* the user.

It is essential that the *choice of media* to communicate with users is adequate and capable of effective portrayal (Prazeres and Clarke 2003). Data can be portrayed in a variety of ways including tables, graphs, animations, histograms, pie charts, line profiles, etc. In order to adequately convey the inherent message, the graphics must be accurately perceived. Therefore, an important issue for BECs is effective media selection in order to communicate complex building performance data.

2.3.4.1 Analysis over time

A building is a dynamic entity and as a result, information aiding energy efficiency appraisal techniques requires that it is analysed over time. The portrayal of sets of ratios with respect to time points towards the use of *scatter graphs*. These graphs show how two continuous variables are correlated by depicting their distribution in 2-D space. Curves are superimposed to indicate the trend. An important 'rule of thumb' considers using no more than four lines per graph, with each line having a label (Tullis 1988). This guiding principle is considered and the evolution of BECs graphs is explained in Figure 2-5.

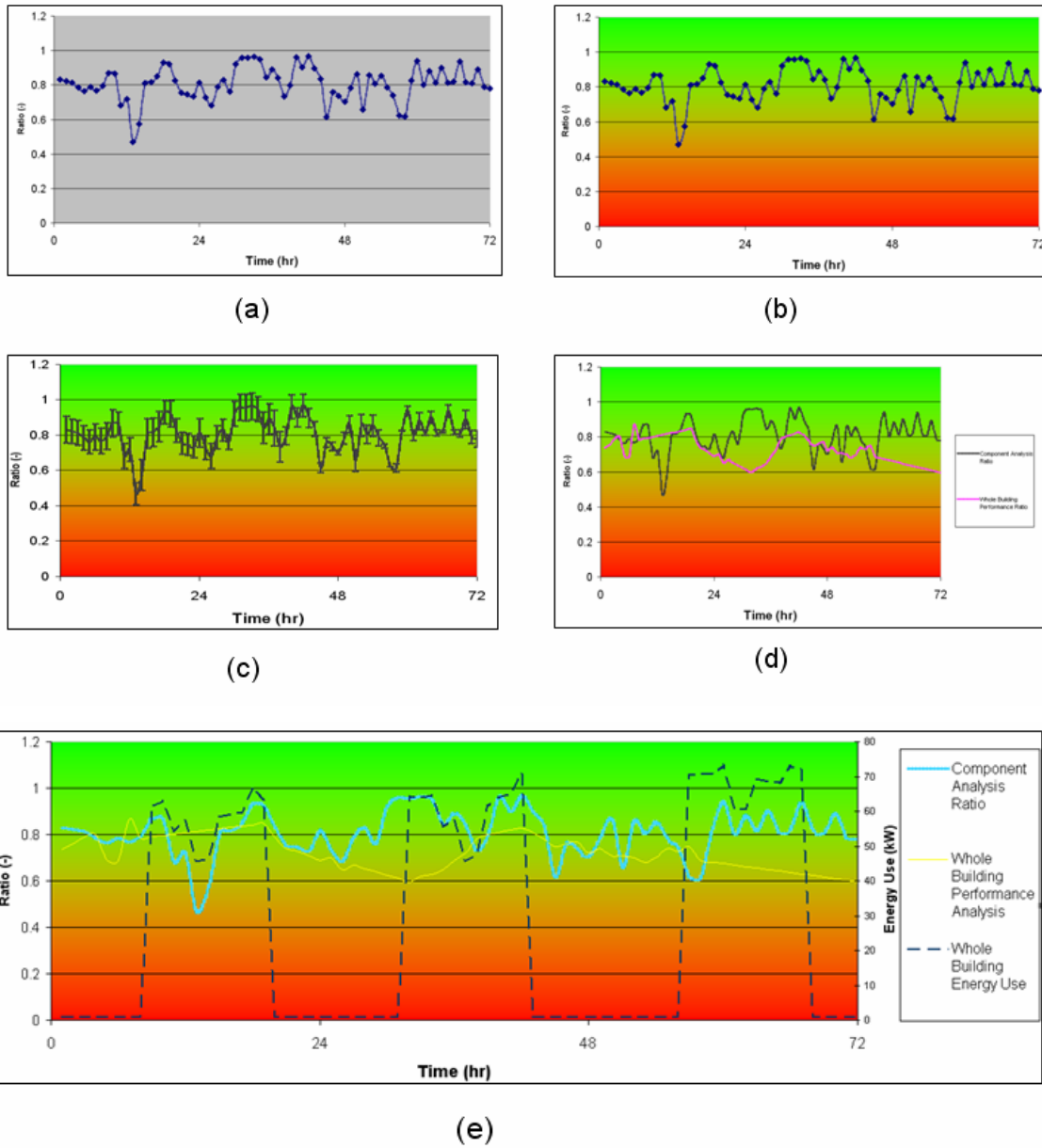


Figure 2-5 – The evolving process of describing the optimal depiction of information for user understanding

Figure 2-5 depicts the wide variety of graphs *considered* for displaying pertinent information using BECs. All graphs use the X-axis to display time and the primary Y-axis (left hand side) displays the values of BECs:



- 1) *Graph (a)*. This graph contains one scatter curve depicting the correlation of BECs' values over a three day period for a specific component. Note the clear labelling of axes, data and gridline.
- 2) *Graph (b)*. This graph introduces background colour to highlight the importance of value (green = efficient, red = inefficient). The purpose of these graphics is to alert the user. BECs values that fall into the *red* area are considered to be poorly performing systems.
- 3) *Graph (c)*. This graph introduces error bars. A typical building runs under many disparate operational load schedules. Even during 'off' times of operation, a facility will still have many additional loads which are fuelled using existing energy reserves. However, energy consumption is proportionally low, and the values of BECs during these times are not as significant. The purpose of these error bars is to communicate this issue to users. Ratios during these times can often be considered superfluous while undertaking system evaluation. However it should also be noted that error bars appears to give the graphs a 'cluttered' appearance and detract from the main message.
- 4) *Graph (d)*. It is essential that the correlation between specific component performance and whole-building (holistic) performance is appreciated. In order to remedy the oversight of 'not considering holistic building performance', this graph contains an additional scatter curve correlating BECs values for holistic energy-use.
- 5) *Graph (e)*. A secondary Y-axis for a third scatter curve is added which correlates holistic energy-use (measured in kilowatts) against the same X-axis (time). This is important as it discriminates between significant values of BECs ratios during operation hours. The message conveyed is similar to the error bars depicted in *Graph (c)*, however this form of portrayal is considered to be less cluttered and more user-friendly.

Graph (e) is selected as the template for all BECs graphs due to its simplicity; it communicates the message in a clear format however it is underpinned by rich sets of energy related data.



2.3.4.2 Ratio Visualisation

The key to BECs' success is the capability to depict a view that is both meaningful to the AEC community and to society at large. These views incorporate data that illustrate the result of actual performance versus 'expected performance'. As seen in Figure 2-5 (e), a BECs' scatter graph depicts the dynamic behaviour of the building.

2.3.4.2.1 *Bounds*

A BECs values conveys a message of building energy-use performance. These values should fall within the range of zero to one (0 to 1). BECs values that lie closer to 1 describe levels of superior performance.

Any BECs values greater than one delineate a scenario whereby the performance of the building has surpassed an ideal. This is not envisaged to be possible with adequate selection of the 'ideal' performance. Values for the ideal are discussed in greater detail in Section 2.3.3.2.1.

2.3.4.2.2 *'No-operation' times*

A building rarely, if ever, has 'absolute-zero' periods of operation. Building systems such as security lighting and other core essentials are constantly 'on' through the day. However, during these hours, it is often safe to ignore the BECs values calculated for the building (it should be noted that this may vary between case studies). For example in Figure 2-6, we can see that the energy required by the building is low during the periods highlighted by the yellow circles. As a result, BECs values should be ignored. It is only during the energy intensive periods of operation that BECs values should be assessed. Defining the cut-off point for ignoring BECs values is at the discretion of project team.

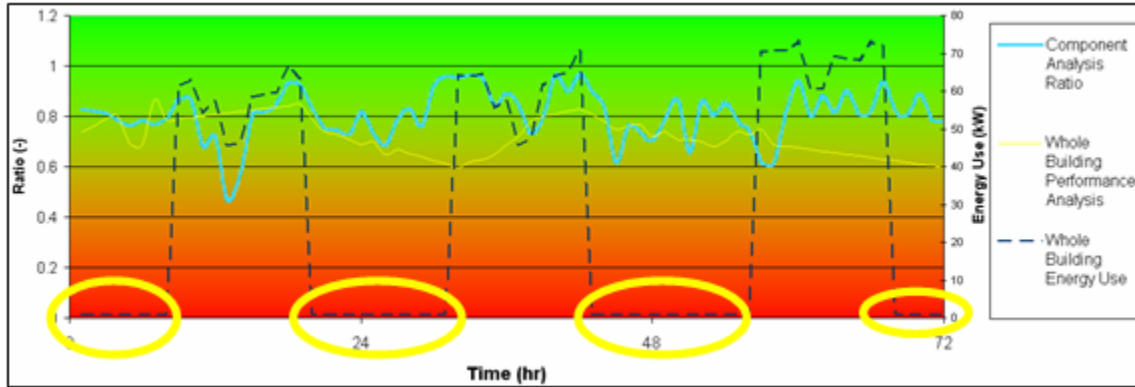


Figure 2-6 – BECs scatter graph depicting ‘low-load’ operational time ranges when BECs values can be ignored

2.3.4.3 Component/Strategy Selection

Selection utilising BECs values involves a whole building appraisal approach highlighting ways of increasing holistic building performance through effective design decision support. Average values of BECs ratios during *normal operation* hours or periods of high energy-use (Figure 2-5(e)) are generated. These values are referenced as input for *column graphs* which aid system component/operational strategy selection. Column graphs depict values of a single continuous variable for multiple separate entities. The columns are grouped according to the system configuration to aid appraisal techniques and user understanding.

Figure 2-7 depicts a sample analysis using BECs values for selection purposes. The operational performance of four disparate systems is analysed over a ‘pre-selected’ time-period. Despite System #4 displaying the maximum average BECs value, it does *not* lend itself to the maximum average BECs value for holistic performance. System #3 should be selected after BECs analysis due to greater levels of holistic performance. Due to this simplicity, this methodology for decision-making is applicable to system experts and non-experts alike.

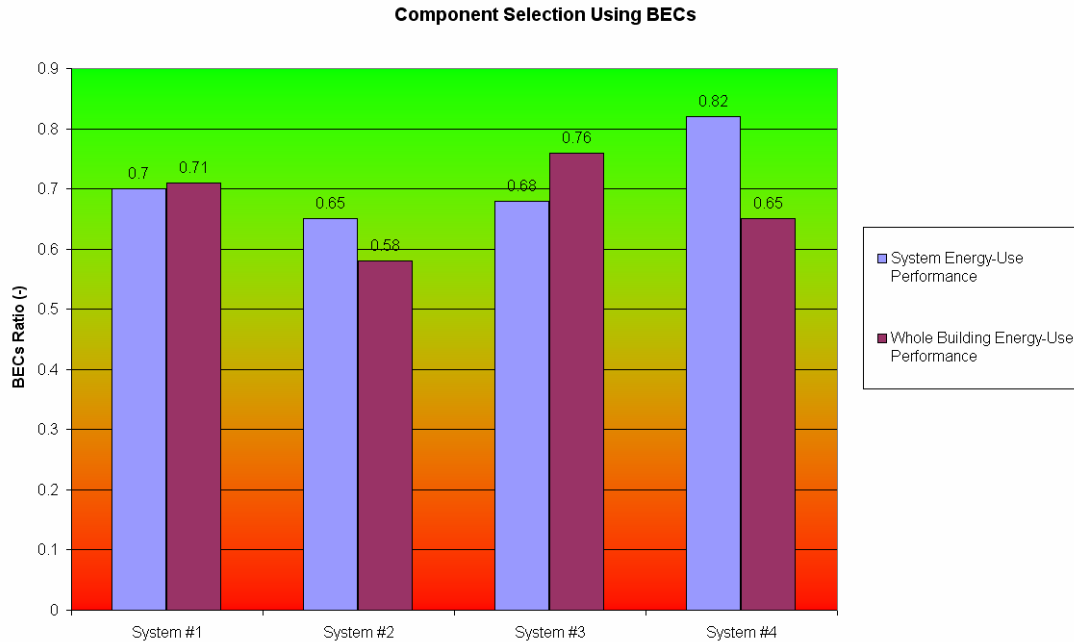


Figure 2-7 – Alternative component selection using BECs appraisal over component and whole building resolution levels

2.3.5 Computer Integrated Construction

As the manufacturing and construction industries increase their global growth, there is a mounting demand for the exchange of digital product definitions. An environment offering both the use of computing for all kinds of application and the integration of these applications - by data transfer networks and transfer standards - is commonly referred to as Computer Integrated Construction (CIC). Integration in the context of CIC refers to efficient and seamless information *sharing* and data *exchange* using IT as the enabling medium (Best and Valence 1999). Such a suite is commonly referred to as interoperability.

Employing a suite of ‘interoperable’ tools could greatly: expedite the buildings design and construction processes; reduce the capital cost; reduce the time taken during the design and construction phases; and greatly improve “habitability and environmental impact of these buildings” (Selkowitz et al. 1996).

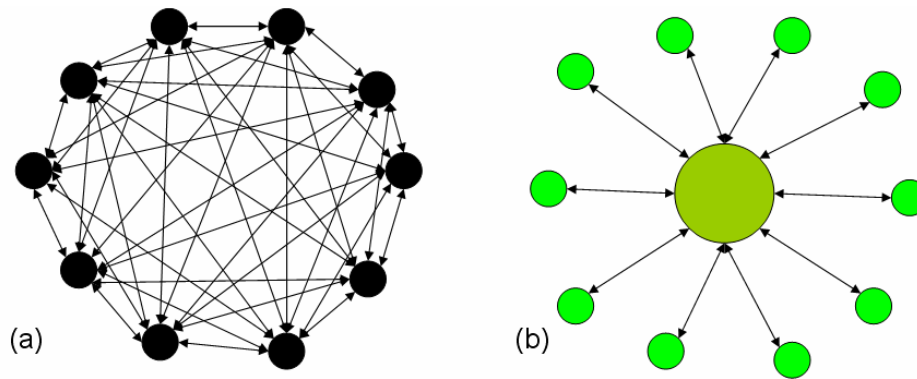


Figure 2-8 – The disparate modes of communication between software tools. (a) Depicts the cumbersome use of interfaces between a myriad of applications. (b) Depicts the use of an open data model supporting integrated design processes.

Major industry products including aircraft, ships, buildings and industrial plants have lifetimes stretching over decades. These commodities are becoming intrinsically complex as they evolve with greater functionality. The development of these products requires vast quantities of information from many disparate design team partners. As a result, product data must be accessible to a myriad of computer applications. The burdensome task of re-creation and duplication between proprietary software utilised by these design teams leads to inconsistencies and does not add any form of value to the product. One solution is to develop interfaces between applications (Figure 2-8 (a)). However this practice rapidly produces large numbers of translators. Four applications requires 12 interfaces, 10 applications require 90 interfaces, and so on. The problem is compounded by the constant maintenance required to each of the interfaces if the data model is altered in any one of the applications. The solution to this problem is highlighted in Figure 2-8 (b), this figure depicts an integrated information model which supports multiple views of product data for different applications. Accordingly, the administrative cost of ensuring that data are consistent between the many other disparate applications is avoided.

2.3.5.1 Integrated Environments – A Success Story for the Aerospace Industry

Typical aerospace projects involve a number of major international partners with up to 10,000 suppliers and hundreds of customers around the world. This kind of product may



be in service for the next 30 years or more and the customer demands accurate information on delivery and throughout its life cycle. In order to meet this challenge, the industry has adopted digital definitions of the product, offering improved accuracy & quality, greater speed, reduced costs of rework and the ability to perform additional analyses of the models before production. This digital product data can be used throughout the product's life-cycle in any manner deemed appropriate and without compromising the integrity of the information.

The use of integrated environments as depicted in Figure 2-8 (b) was successfully implemented by Boeing and its engine suppliers during the process of integrating engines and their complex plumbing into an airliner. This replaced the expensive practice of physical mock-ups. A similar practice expedited design communication and assembly structures for the Eurofighter project between the four national partners (Mason 2002).

2.3.5.2 Interoperable Environments – Building Information Model (BIM)

A suitable environment must be selected in order to streamline the assessment of a building. Simulation-based programs are excellent tools for assessing and mitigating the energy requirement for a myriad of buildings. However there is an associated high cost involved when gathering the large volumes of data required for robust and valid simulations of a facility. The reason for limited uptake in simulation tools as a driver for building design is that they do not 'fit' into the design process (Papamichael et al. 1997).

As the BLC transcends each phase of the BLC, duplication of data for input into these models is labour intensive, time consuming, error prone and requires skilled analysts in both simulation and building technology (Mourshed et al. 2003). This issue is compounded by the disproportionate increase in data required as simulation capabilities grow. This is pertinent given the high resolution of analysis undertaken by the proposed assessment technique. Accordingly, the BECs methodology requires the use of computer integrated environments facilitating a myriad of functions. Specific examples include:

- 1) an accurate bill of materials and cost estimation process (Ibrahim et al. 2004);
- 2) building structural analysis (Romberg et al. 2004); and



- 3) automated model input file configuration for whole building energy simulation (Papamichael et al. 1997; Bazjanac 2004; Neuberg et al. 2004).

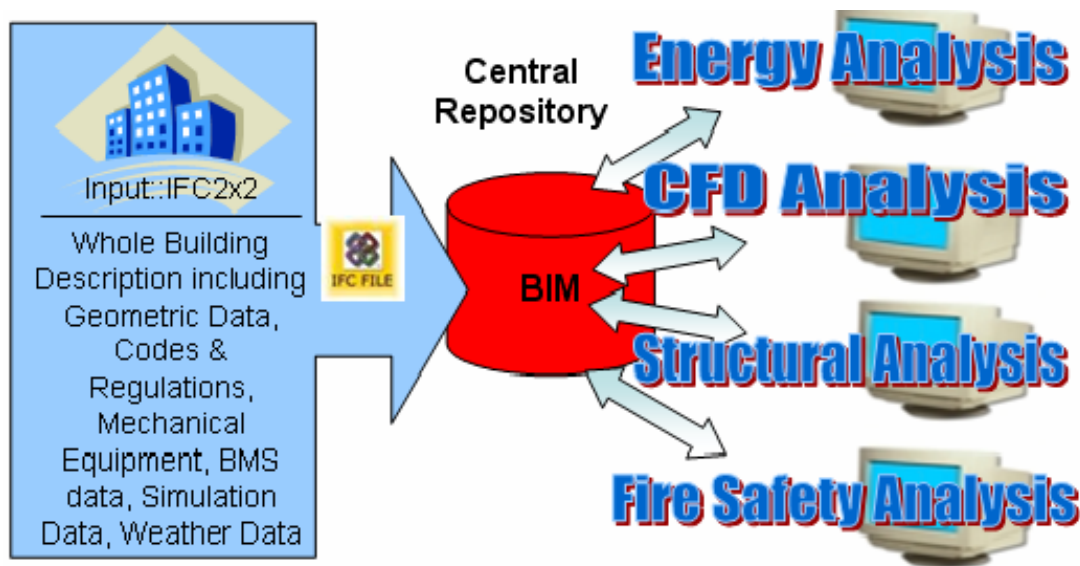


Figure 2-9 – High level view displaying an open data model underpinned by Industry Foundation Classes (IFCs) facilitating integrated processes from the AEC&FM community

Open and interoperable environments facilitate the use of data elicited from one central repository and guarantee consistency for information delivery. This form of data model allows each participant to employ disparate tools specific to their needs (or domain) without compromising or corrupting project data (Figure 2-9). By requesting digital project information that can be easily kept up to date, building project personnel have access to information for ongoing design, construction, building maintenance and operation. The information is created *once* and it is available throughout the BLC providing secure, consistent, concurrent and accurate access to data. This capability presents the ideal opportunity to execute building life-cycle performance-based assessment techniques.

2.3.5.2.1 BIM Process

Electronic documents are just one single component in the BIM process; it is really about pertinent information use, reuse and exchange. A BIM is underpinned by the concept of product modelling. As such, it is possible to represent the building in terms of parameters



that reflect the *descriptive* and *performance* characteristics of the facility. When a 3-D model is linked with building information, design teams have a faster, higher quality and richer design process. Lower level tasks such as drafting, view-coordination, document generation and schedule creation become automated. When features of the building are altered, they are automatically updated in the disparate views of the same buildings. The BIM process moves the computer aided design beyond a mere mimicking the drafting process for the first time.

2.3.5.2.2 BIM Functions

Adequate documentation of design rationale and philosophy is critical to facilitate appraisal at various life cycle stages and provide decision support. This includes documentation of the *alternative* solutions that were investigated to ensure “future modifications to the building do not negate or inadvertently alter key elements or features critical to the intended performance of the building and its systems” (Bergeron and Bowen 2001).

The BIM serves several key functions:

- 1) *Building Summary*. A BIM contains information about the building’s construction details, installed HVAC and a performance history of energy-use;
- 2) *Hub Document*. A BIM contains links and pointers to several disparate sources of information relevant to the building (i.e. links to weather files, building codes for design, etc.);
- 3) *Source of information and training*. A BIM provides a medium for augmenting analysis data for daily management and operation of the facility. Information from this BIM can be employed to test-bed other operations in order to uncover the highest degree of building management effectiveness;
- 4) *Dynamic and open documentation*. Any changes to the building can be readily documented in a BIM for ease of retrieval at a subsequent data. A log of design philosophy and performance history facilitates continual fine-tuning of the building.



2.3.5.3 Industry Foundation Classes (IFCs)

All computer programs deal with some form of data, as a result they all utilise some form of underlying data model. However, these data models tend to be proprietary in nature and do not facilitate the seamless transfer of data between software tools. The lack of a common product model to describe the many disparate views employed by project participants can be identified as a main difficulty in overcoming the fragmented nature existing within building industry (Treeck et al. 2003). Therefore, a natural step in leveraging open data sharing among software tools (and creating BIMs as a result) requires the adoption of Industry Foundation Classes (IFC) compliant software. This promising solution offered by International Alliance for Interoperability (IAI 1995), serves as non-proprietary object orientated description of BIM data to ensure software interoperability in the building industry.

The IFC effort closely parallels another international product data standard (ISO 10303), otherwise known the Standard for the Exchange of Product Model Data (STEP). STEP is a proven standard and consists of a comprehensive series of documents providing industries with the capability to exchange and share information used to define the product (Mason 2002). Using the EXPRESS data definition language (Part 21) provides a complete, unambiguous, computer-interpretable definition of the physical and functional characteristics of a product throughout its life cycle. This file format makes it suitable not only for neutral file exchange, but also as a basis for implementing and sharing product databases and archiving.

IFCs were developed to support interoperability across the individual, discipline-specific applications that are used to design, construct and operate buildings. IFCs capture tangible objects such as walls, doors, windows, etc. and intangible building data such as schedules, activities, space construction costs, etc., across the entire project life cycle. The latest release of the IFC data model (at the time of this research) – termed IFC2x2 Addendum 1 – supports interoperability for ‘post-CAD’ applications. Accordingly, this data model with its standard set of rules for data storage, data exchange and protocols has reached a level of maturity making it extremely supportive to ‘downstream’ industry process. Most importantly in the view of this research, it provides an ideal platform to set energy simulation (Bazjanac 2003) and energy monitoring requirements of a building.



2.4 Chapter Summary

The nebulous task of achieving high levels of energy efficiency in a building is not an easy undertaking given the impact and inter-dependence on so many heterogeneous agents. This is leading to many facilities not achieving high levels of energy performance. The reasons for this problem are rooted in inadequate communication throughout the BLC processes, inadequate communication between design aids, inadequate training of building managers and uneducated clients who are left to deal with the consequences. This is leaving the built environment feeling unhealthy, uncomfortable, energy intensive and ultimately, unproductive.

As a result, this thesis proposes a new methodology which employs existing technologies for application throughout the BLC. This methodology, referred to as the BECs methodology, attempts to address each of the flaws listed above and deliver the industry an easily understandable language of communication for all project stakeholders.

The proposed methodology is a systematic qualification of building energy performance. It is calculated by quantifying ideal energy use versus expect/actual energy use. Data for these calculations are leveraged from a BMS and a whole building simulation tool. The resulting message from the calculation stages is communicated in the form of scatter graphs (for a view of performance over time) and column graphs (for component – or operational strategy – selection).

The methodology itself is underpinned by an interoperable environment. This is vital as it offers a central data model facilitating seamless and concurrent access to building information. This breaks down the barriers between disparate software utilised during the BLC stages.





Chapter 3

Building Effectiveness Communication Ratios (BECs)

Chapter 3 discusses the details and semantics of the proposed energy-use assessment framework, termed ‘the BECs methodology’. The methodology’s ratio values, calculated throughout the iterative BLC phases, translate complex definitions of sustainability for energy efficiency and depict universally understandable views underpinned by ‘industry-standard’ building appraisal tools. Accordingly, they convey distinct messages of performance to different project stakeholders to aid the decision making process.

“Everything should be as simple as possible, but not simpler”

- Albert Einstein



3.1 Introduction

Building Life Cycle Phase	Function
Early Design Phase	• HVAC System Selection
Design Development	• System's Component Selection
Detailed Design Phase	• Updated Performance Prediction • Insurance of Design • Cost-cutting Impact Evaluation
Construction	
Commissioning Phase	• Updated Performance Prediction • Insurance of Installation
Operational Phase	• Actual Performance Evaluation • Design Feedback • Project Evaluation

Figure 3-1- The iterative processes required throughout the BLC to ensure levels of high energy-use performance

A myriad of functions comprise the iterative phases of the BLC. Figure 3-1 depicts a simplistic view of the building world that is specific to the BECs methodology. The functions supported by the BECs methodology are outlined along with their corresponding phase of the BLC. The aim of the BECs methodology is to provide project stakeholders (client, architect, structural engineer, HVAC design engineer, etc.) with an enabling communication framework for supporting the decisions making processes at each of the stages outlined in Figure 3-1. This research considers that five key concepts are necessary in order to provide this enabling methodology. These include:

- 1) performance-based assessment;
- 2) performance metric tracking;
- 3) project stakeholder communication;
- 4) application of the methodology across the entire BLC; and



- 5) an interoperable software environment facilitating access to building information data.

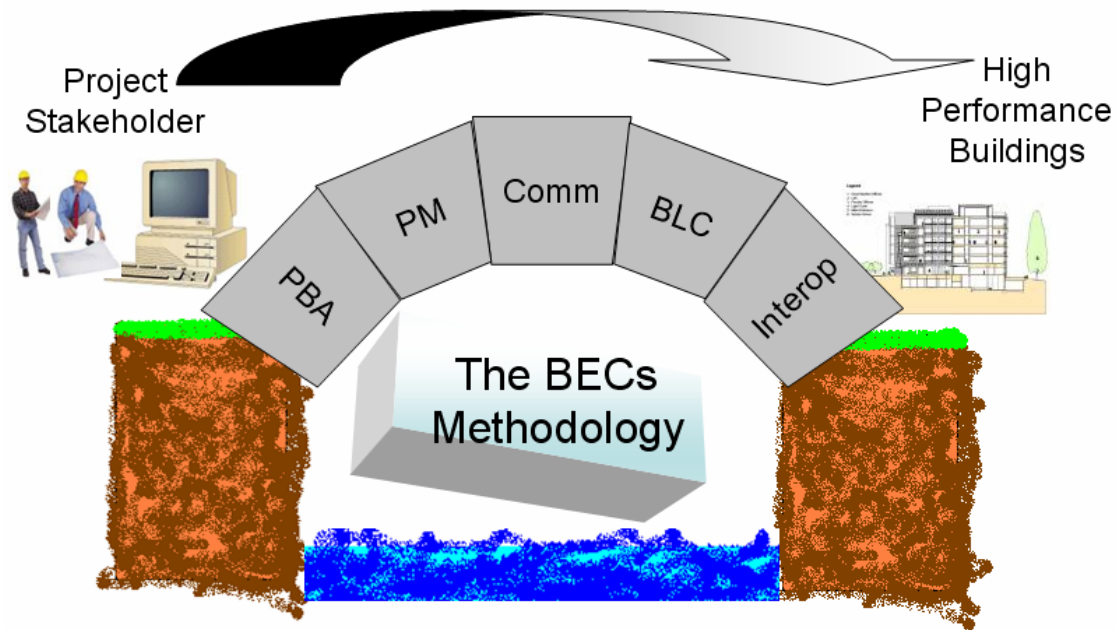


Figure 3-2 – The five key concepts required by the BECs methodology to effectively use existing industry expertise to produce high performance buildings

The form and interrelationships of the concepts are equally significant. An arch bridge is employed as the metaphor to convey the ‘structure’ of the proposed methodology (Figure 3-2). In order to outline why the metaphor of an arch bridge was employed to convey the concepts underpinning the BECs methodology, it is important to describe the ‘form’ of an actual arch bridge.

If stone blocks are fitted correctly to form an arch, a span – normally not traversable using a lone stone – can be negotiated with ease. Additionally, it is not merely the stones that keep the bridge in place, but also the bridge’s own weight. Therefore, the bridge is underpinned by these stones, but it also supports these stones.

Within the BECs methodology, each one of the five key concepts may be represented by a single stone. On its own, each concept is self-contained and can enable a plethora of processes, *but not the goal itself*. However, if all concepts are employed, the methodology may ‘bridge’ the gap and aid the design team to produce a high-



performance building. If one of the stones is removed, the bridge becomes unstable and falls down. Similarly, if one of the concepts is removed, then the methodology will not be successful as an enabling framework for moving towards increased levels of building energy efficiency. Finally, much like the weight of the bridge supporting the stones, the BECs methodology supports the concepts which underpin the framework (Section 3.3).

3.2 The BECs Methodology

Many methods have been proposed for assessing a building's sustainability (Section 1.5). However, as discussed in Section 1.5, there is a requirement for a tool capable of assessing or predicting the operational energy-use performance of the building throughout the BLC which would provide decision-support for performance related matters.

In their book titled 'Specifying Buildings', Emmitt and Yeomans consider distinct four factors which place constraints on human decision making (Emmitt and Yeomans 2001):

- 1) an overload of information which makes the key concept difficult to appreciate;
- 2) a limit to the amount of information individuals and organisation can recall;
- 3) inadequate comprehension of the information at hand; and
- 4) inadequate communication (different groups developing their own frameworks which are not universally appreciable by non-specialised individuals).

Accordingly, the proposed methodology aims to aid the communication process through forcing teams with universally understandable building energy-use yardsticks of performance.

In order to develop the yardsticks of performance, the methodology builds on the principles developed in two distinct strands of research. Extensive research considers that in order to mitigate the energy-use of the building stock, it is vital that strategies and technologies within facilities are assessed on an *individual project basis* (Papamichael et al. 1997). Additionally, the yardsticks of performance are measured by a comparison of performance with an *ideal*, as suggested in research developed by Federspiel et al. during



the development of “Model-based Benchmarking” techniques incorporating effectiveness ratios (Federspiel et al. 2002).

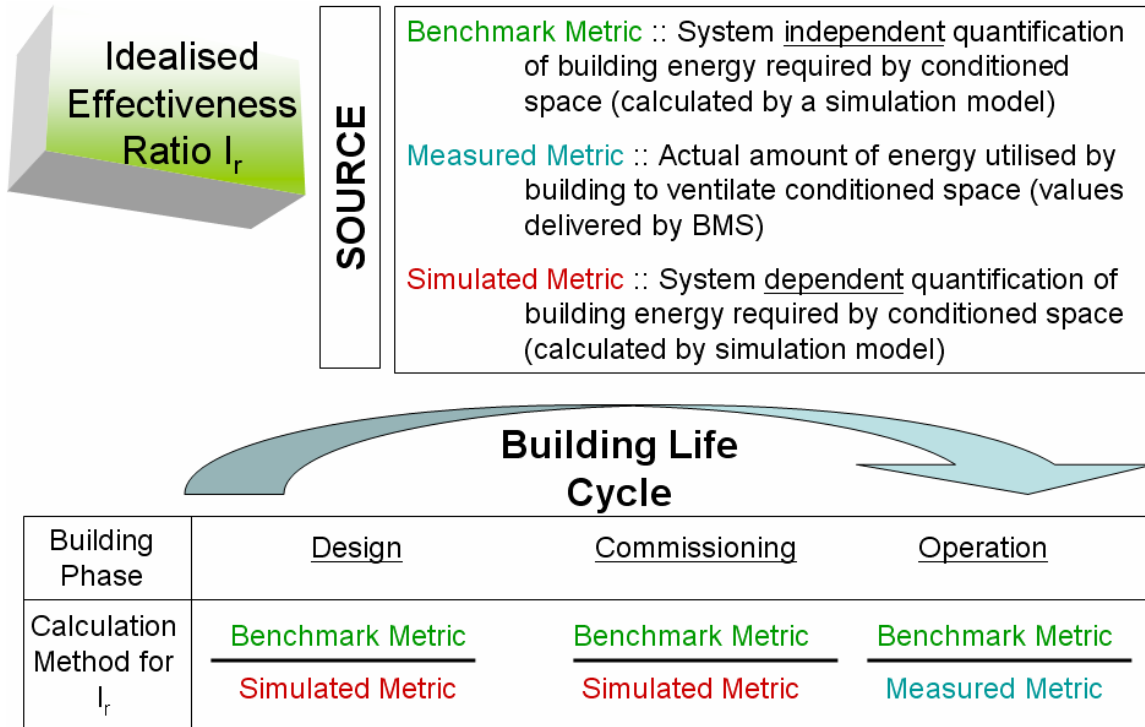
With these principles in mind, each building assessed by the BECs methodology is evaluated individually for qualification of energy-use performance. This is facilitated through the comparison of predicted/measured energy-use with ideal energy-use for that particular building. This may be carried out for individual components or for the whole building. However, if a component is under assessment, it is always necessary to assess the holistic performance of the building (Section 2.3.4.3).

Sections 3.2.1 and 3.2.2 describe two distinct effectiveness ratios proposed in this research work. The first effectiveness ratio (Idealised Effectiveness Ratio (I_r)) is for use throughout the building life cycle. Its primary role is to support decision making at the design phase of the BLC, however, it has many additional uses. The second effectiveness ratio (Performance Effectiveness Ratio (P_r)) is for use post-occupancy evaluation of operational performance. Its primary use is to act as a quantitative target for the management team in order to operate the building as effectively as possible. Finally, Section 3.2.3 describes the storage of BECs values in a central location accessible by all project stakeholders at the upstream and downstream phases.

3.2.1 Idealised Effectiveness Ratio

It is a view within some elements of the industry that designers are often “indifferent to the energy performance of buildings, or even in conflict with energy-efficiency goals” (Hitchcock et al. 1998).

The Idealised Effectiveness Ratio (I_r), the first of two BECs values, addresses this key inadequacy. I_r values are performance metrics which provide continuous design feedback on the effectiveness of building energy-use throughout the BLC. This is a vital means of ensuring energy-conscious solutions remain uncorrupted *philosophies of design* as the project progresses from initiation to completion. Values of I_r provide a yardstick of building energy-use performance to support design decisions (however this enabling performance metric provides additional functionality (Figure 3-3)).



Equation 3-1 - Calculation of I_r values throughout the BLC

Calculation of I_r values may be facilitated throughout the BLC through comparison of ‘predicted/measured energy-use performance’ with ‘ideal energy-use performance’ (Section 2.3.2). The ideal version of the building is defined by values leveraged from the whole-building benchmark simulation model (Section 2.3.2.1.1). The focus for the project teams throughout the BECs methodology is to achieve a level of energy-use ‘as close to this target as possible’ while maintaining adequate levels of thermal comfort.

The most significant stages in the life-cycle of I_r are:

- 1) I_r (early design): the early design phase;
- 2) I_r (detail design): the detailed design phase;
- 3) I_r (commissioning): the commissioning phase; and
- 4) I_r (operational): the operational phase.



Building Life Cycle Phase	Function	Performance Communication to each Project Stakeholder				
		Client	Design Team	Facility Manager	Occupants	Community Knowledge base
Early Design Phase	• HVAC System Selection	✓	✓		✓	✓
Detailed Design Phase	• System's Component Selection		✓		✓	✓
	• Updated Performance Prediction	✓	✓		✓	✓
	• Insurance of Design	✓	✓		✓	✓
	• Cost-cutting Impact Evaluation	✓	✓		✓	✓
Commissioning Phase	• Updated Performance Prediction	✓	✓		✓	✓
	• Insurance of Installation	✓	✓		✓	✓
Operational Phase	• Actual Performance Evaluation	✓	✓		✓	✓
	• Design Feedback		✓		✓	✓
	• Project Evaluation	✓	✓	✓	✓	✓

Figure 3-3 – The functions of I_r values pertinent to each project stakeholder throughout the BLC

Values of I_r are employed throughout the BLC to ensure the design's performance goals remain uncorrupted. Values of I_r may be employed to support the decision making process at these iterative phases. They convey distinct messages to different project participants (Figure 3-3). The functions, calculation and messages conveyed to project participants are wholly delineated in the following subsections.

3.2.1.1 Early Design Phase

The energy saving potential of the building is dominated by the decisions made at the earliest phases of the BLC (ASCE 2004). The BECs methodology employs whole building energy-use simulation tools to generate values of I_r for decision support at the early design phase of the BLC.

During the design stages of a project, design teams with inherently high levels of domain knowledge and expertise are engaged in the building planning process (Clements-Croome 2004). Initial descriptions of the building must be configured in these models. The domain knowledge of the all project stakeholders can expedite this process by using



educated approximations for boundary conditions (thermal properties in building’s form, infiltration levels, space-use, etc.).

3.2.1.1.1 HVAC System Selection

At this stage of the BLC, the project team must choose the HVAC system which will mechanically service the building. Values of I_r are calculated through comparison of *alternative* simulated metrics (Section 2.3.3.2.2.1) with the benchmark metric (Section 2.3.3.2.1.1). Each one of the simulated metrics offers a preliminary indication of the predicted performance of these HVAC strategies. Accordingly, values of I_r enable design teams to distinguish between systems offering superior levels of performance.

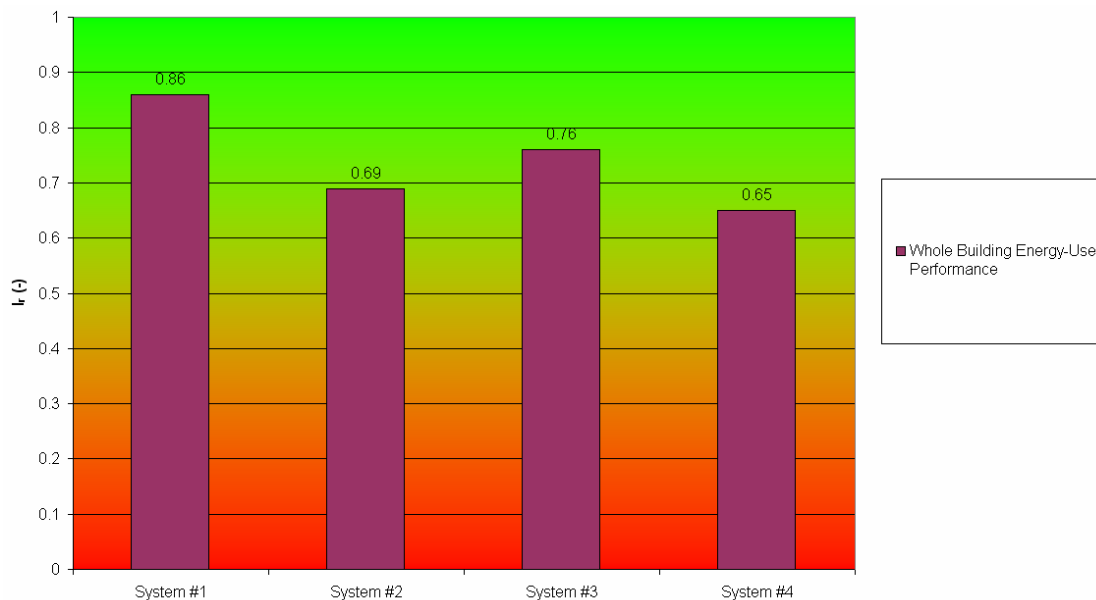


Figure 3-4 – Highlighting alternative systems and their corresponding performance evaluation during the early design phases

Figure 3-4 depicts a sample graph where alternative systems were evaluated utilising I_r as a distinguishing medium for decision support. The sample figure shows that ‘System#1’ will offer the best performance.

As depicted in Figure 3-3, the message of performance is communicated to the client, the design team and the future building occupants so that:



- 1) The client can appreciate the selection, as the ratio values convey downstream operational performance. As a result, even though ‘System #1’ from Figure 3-4 may require a higher capital cost, the effectiveness of operational energy-use will be far superior. Values of I_r convey a message of ‘increased operational savings’ to this project participant.
- 2) The values of I_r aid the selection of the appropriate HVAC strategy which best suits the facility in hand. This provides the HVAC design team with a pragmatic framework for system selection and an enabling tool for communicating the selection rationale to all project stakeholders.
- 3) All BECs calculation models have factored adequate levels of thermal comfort as boundary conditions during the calculation process as prescribed by environment guidelines (ANSI/ASHRAE 1999; CIBSE 1999). As a result, all systems under evaluation are envisaged to provide adequate comfort conditions for the occupants. Each time BECs assessment has an inherent message that adequate thermal comfort conditions have been factored into the evaluation.

3.2.1.2 Detailed Design Phase

Employing the BECs methodology provides the support for an integrated design approach to decision-making. The functionality of the framework during the detailed design phase is outlined in the following subsections. This integrated approach may take place over several meetings. However, it is capable of universal appreciation by all project stake-holders. This will aid the delivery of a superior product for all stakeholders concerned (Section 3.3.3).

3.2.1.2.1 System Component Selection

Before the ‘detailed design stage’ of the BLC, one particular HVAC system will have been selected to mechanically service the building with adequate thermal comfort conditions. The interrelationship of the performance characteristics of components within the building is critical. Decision-makers often do not clearly understand the interconnectedness of performance problems (Hitchcock et al. 1998). When optimising the performance of a component or its subsystem levels, the building must always be

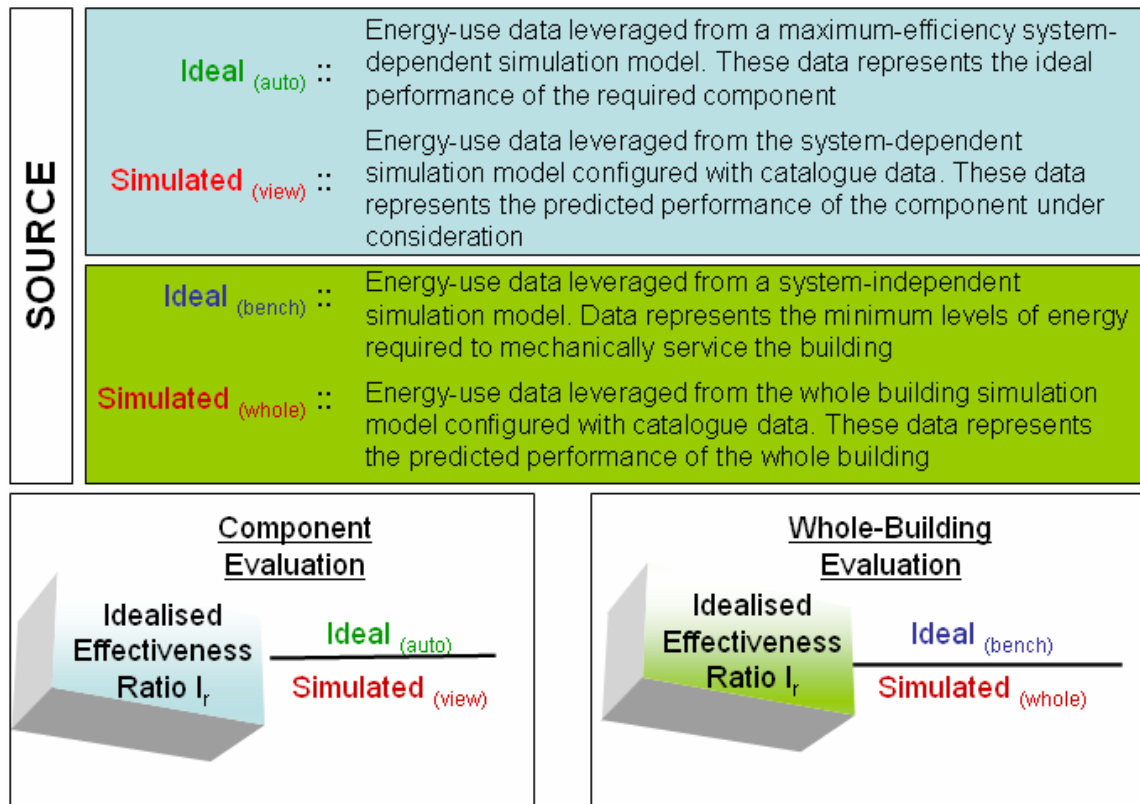


viewed from the “building-as-a-whole” (or holistic) level (as seen in ‘Component Selection’ in Section 2.3.4.3). As a result, two distinct values of I_r must be calculated (Equation 3-2):

- 1) one for ‘optimised component selection’; and
- 2) one for ‘optimised holistic performance’ .

It is always necessary to ensure that only components that offer the maximum levels of *holistic performance* are selected.

The selection of optimised components requires a pragmatic approach. A strategy is employed whereby alternative components are assessed in order to choose the most efficient model. Figure 3-5 depicts a typical scenario. Values of I_r were calculated for component performance and holistic performance for four separate components.



Equation 3-2 – Calculation of the I_r values required during the component selection phase



The I_r for the component evaluation is calculated by a comparison of the predicted performance of the component (Section 2.3.3.2.2.2) with the ideal performance for the component (Section 2.3.3.2.1.2). The ideal performance is represented by a fully autosized (maximum efficiency) configuration of the system that is to be installed in the building. As a result, it offers a means of assessing the performance of individual components.

The I_r for holistic performance of the building is calculated by a comparison of the performance of the whole building (Section 2.3.3.2.2.2) with the ideal benchmark for the building (Section 2.3.3.2.1.1).

A sample bar graphs used for specific component selection is depicted in Figure 3-5. As can be seen, despite system component #1 highlighting the second best component performance, it does offer the most superior holistic performance. Accordingly, it should be selected for use within the building.

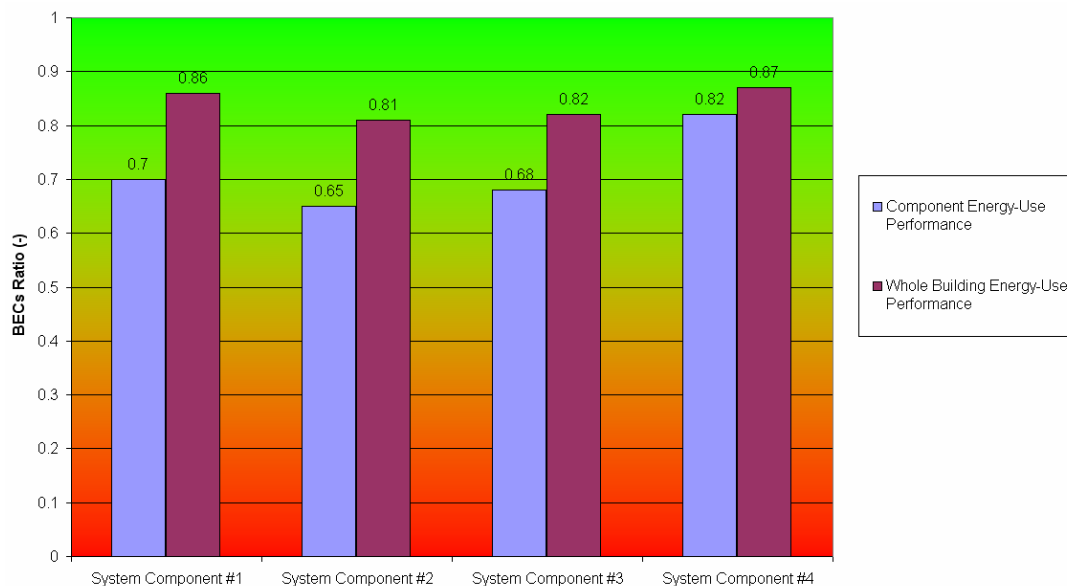


Figure 3-5 – Component Selection Bar Graph during the detailed design phase

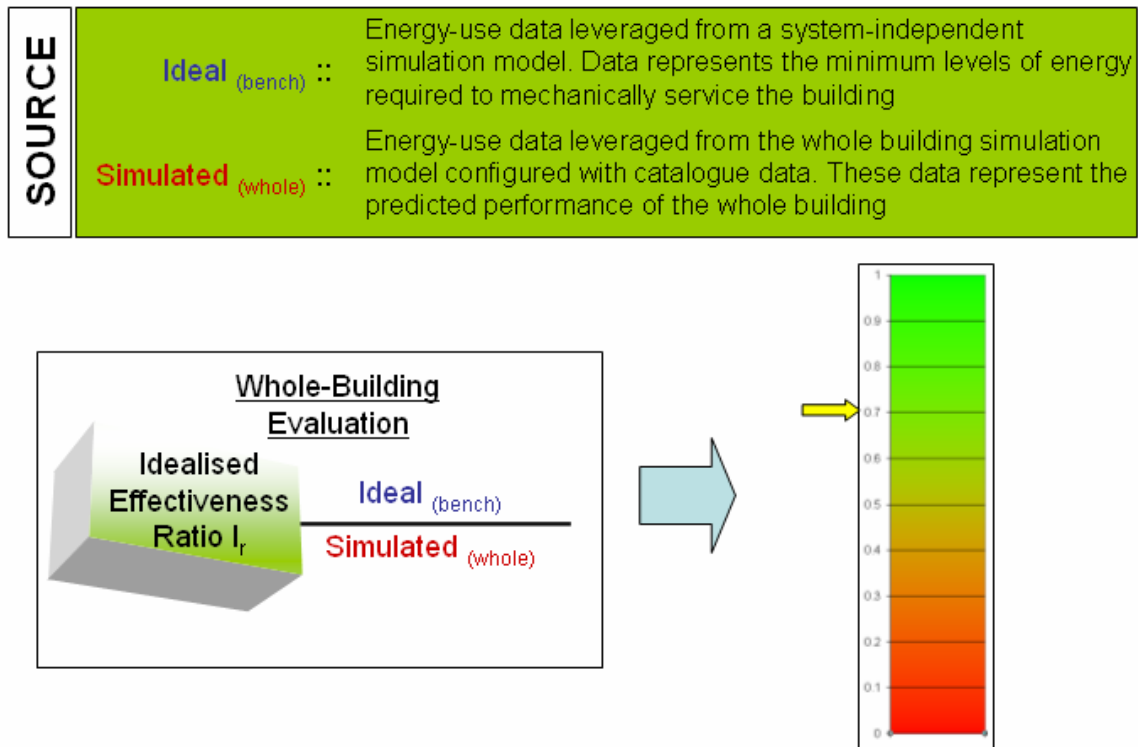
As seen in Figure 3-3, these values communicate *messages* to two project participants:

- 1) The HVAC design team employs values of I_r to ensure an optimised selection scheme throughout the detailed design phase. Additionally, if this selection



- process is queried, these values provide effective proof of proficient selection methods.
- 2) Values of I_r factor the internal environmental conditions (e.g. temperature, RH, etc.) required to achieve adequate thermal comfort for building occupants.

3.2.1.2.2 Updated Performance Prediction



Equation 3-3 – Calculation method for I_r for an update of whole building performance during the detailed design stage

In order to evaluate the performance of the design team during the detailed design stages, values of I_r may be calculated to provide an update in predicted energy-use performance (Equation 3-3). These values offer a mature prediction of the envisaged building performance. This message of predicted performance is communicated:

- 1) to the client (for the prediction of operational performance of building energy-use);



- 2) between the design team members (to evaluate their own design performance);
and
- 3) to the building occupants (as values of I_r account for the conditions required to achieve adequate thermal comfort for building occupants).

3.2.1.2.3 Insurance of Design

At the end of the detailed design phases, the HVAC design team will be unable to make any alterations to the design. Accordingly, values of I_r can provide an ‘insurance of design’ for these project stakeholders. The values calculated for the whole building (Equation 3-1) provide a prediction of building energy-use operational performance.

If the building is operated and managed as per design intent, the minimum predicted performance for downstream operation is highlighted by these I_r values. However, if any alterations are made to the building during the construction or operations phases which may have adverse implications for the energy-use performance of the building, then these values provide an ‘insurance of design’.

Final I_r values for holistic performance furnish the design team with a documented argument that poor operational performance of the building is not their fault.

3.2.1.2.4 Cost-cutting Impact Evaluation

Several cost-cutting exercises will often have to be entertained throughout the early phases in the BLC. Values of I_r may be employed to facilitate an impact study during this cost-cutting exercise. For instance, if high-performance windows need to be cut from the building’s plans, and replaced with lower-performance windows, this may have a large impact on heating and cooling loads. This could result in poorer operational performance and increased operational costs for the client. It is important that *all* project stakeholders understand the impact of cutting any element from the building plans (B&E 2006).

As depicted in Figure 3-6, a bar chart is employed for the impact study. This figure shows an example of a cost-cutting exercise whereby one of the three separate objects must be cut from the building’s plans in order to bring a project back into budget. Each one of the objects is taken out from the simulation models described in Section 2.3.3.2.2.2. Whole building values of I_r are calculated for each case (Section 3.2.1.2.2). Accordingly, the design team may leverage three new whole building values of I_r for aiding the decision



making in the cost-cutting exercise. The bar which denotes ‘the highest values of I_r after the object is removed from the building’ can be considered the best element to be cut from the building plans. This practice offers a method of balancing the necessary cost-cutting exercise with maximising downstream operational performance.

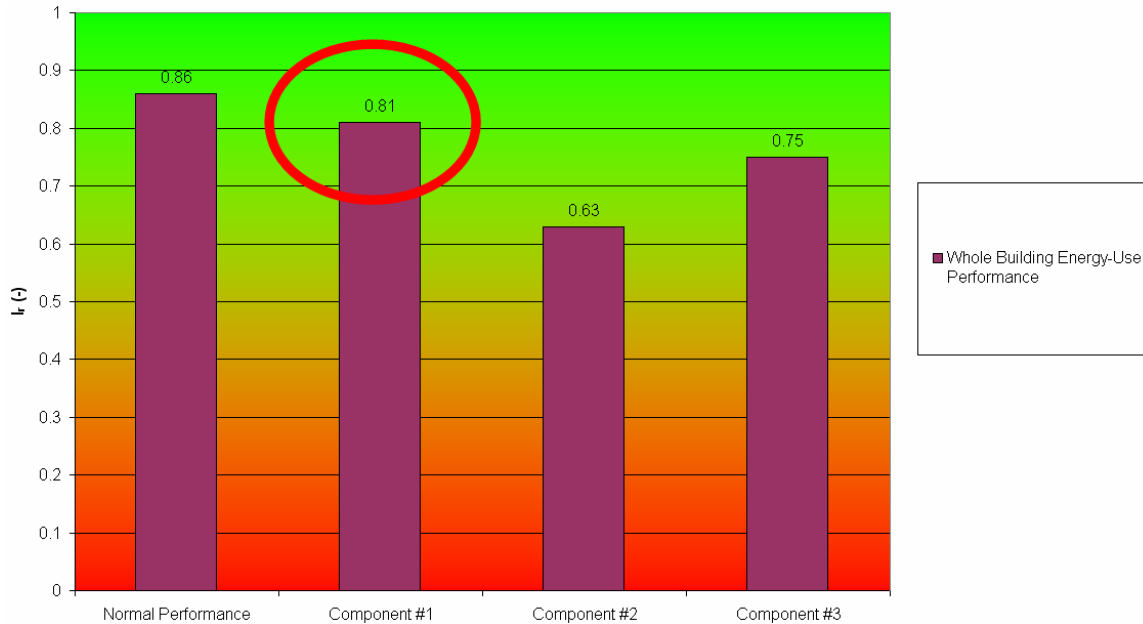


Figure 3-6 – Example of values of I_r which aid cost-cutting exercises

3.2.1.3 Commissioning Phase

Immediately after the commissioning stages of the BLC, values of I_r may be employed for distinct purposes. The calculation process mirror the process in Equation 3-3 with a subtle, but important, difference in the predicted performance. Many sets of data are collected during the commissioning tests which are pertinent to energy-use performance. Process variable's flow information may be configured in the simulation model for calibration purposes (Section 2.3.3.2.2.3). As a result, the predicted performance may be updated when calculating values of I_r . Accordingly, the new values of I_r provide: (1) an updated performance effectiveness ratio prediction; and (2) an insurance of installation.



3.2.1.3.1 Updated Performance Prediction

Values of I_r at this stage of the BLC provide the design team with a preliminary ‘actual’ view of envisaged performance. This prediction of operational performance can be communicated to the design team and to the client, and universally appreciated by all parties. Additionally, it conveys a message of satisfactory thermal comfort to the occupants of the building. These BECs values are stored in the BIM for future referral (to augment the design community’s knowledge-base).

3.2.1.3.2 Insurance of Installation

The most important role played by I_r during this phase of the BLC is that it acts as an insurance policy for the construction and installation teams. If values of I_r (commissioning) differ drastically with I_r (detailed design), an immediate investigation into the ‘reason’ may be sought. For example, if the HVAC design team was not consulted on issues which greatly impacted the operational performance of the HVAC design, then values of I_r (detailed design) provide proof that the original design-brief was not met during installation. Most importantly for the client, until the building elements have been adequately installed and operated, the client can suspend all payments and some form of mediation can be agreed (Chappell et al. 2001).

If the building is constructed and installed correctly, the minimum predicted performance for downstream operation is highlighted by these I_r values. Holistic I_r values furnish these project stakeholders with a documented argument that poor operational performance of the building is not their fault.

3.2.1.4 Operational Phase

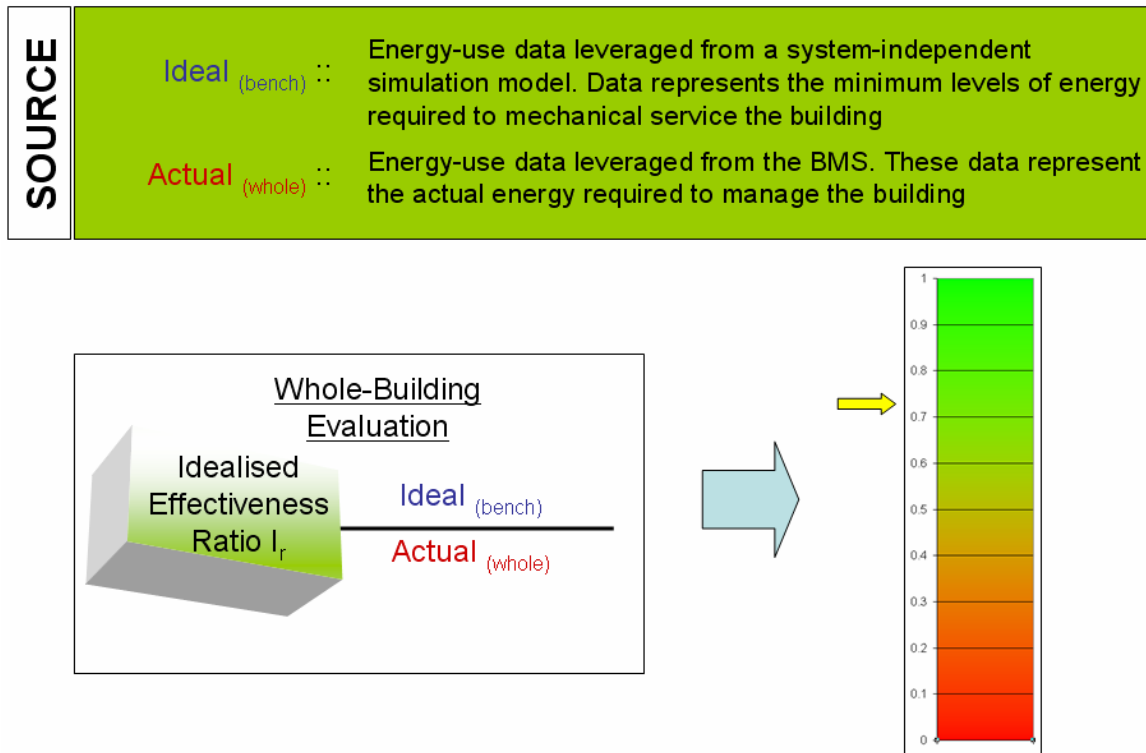
Formal post-occupancy evaluation of the building can be performed by employing the BECs methodology. During the ‘operations stage’ of the BLC, values of I_r (operational) provide the design team with an objective evaluation of actual system performance. These values may only be calculated several months after the building has been occupied. This will leave adequate time for the building to reach a mode that could be considered ‘normal operation’ (ANSI/ASHRAE 1999). Additionally, data must be collected after each of the heating and cooling seasons. Ultimately, values of I_r provide feedback on the



success (or failure) of design decisions. These values may be utilised for influencing design decisions for ongoing operation of the building or for the design of future buildings.

3.2.1.4.1 Actual Performance Evaluation – Operational Phase

As can be seen in Equation 3-4, values for comparison with the ideal level of energy-use are now leveraged from the BMS (Section 2.3.3.1.1). The successes (or failures) of operational performance – coupled with operational design – will be immediately evident from these values.



Equation 3-4 – Calculating whole building values of I_r during the operational phase

These values highlight the downstream operational performance of the building under normal operation conditions. This is important, as design teams rarely evaluate their products post design (Preiser and Ostroff 2001). The operational performance is appreciable by the client who can see that the high-performance goals, stipulated at the beginning of the project, remained intact throughout the BLC. Finally the occupants will



have been delivered adequate levels of thermal comfort as the building's design was guided by principles which mandated adequate levels of thermal comfort (ANSI/ASHRAE 1999; CIBSE 1999). All data are archived in the BIM (Section 3.2.3.2).

3.2.1.4.2 Design Feedback – Operational Phase

Values of I_r provide feedback relating to the effectiveness of performance directly to the HVAC design team and to the client. A building's operational use often moves away from the design specifications as the facility matures (Kiviniemi 2006). However, by retaining the services of the specialised energy consultant, many lessons may be learned during this phase. As a result, assessment of the effectiveness of operation by the HVAC design team is vital so that a knowledge-base can be formed.

3.2.1.4.3 Project Evaluation – Operational Phase

Values of $I_{r \text{ (operation)}}$ for the project may be compared with a myriad of other operational building projects to evaluate the energy-use performance within the pool of projects (Morrissey et al. 2005a). Enabling methods would be required which would resemble the framework suggested by the CalArch environment (Section 1.5.3). However, for the BECs methodology, one building's yearly $I_{r \text{ (operation)}}$ values would be compared with a set of buildings' values.

It is important to note, that unlike benchmarking techniques (Section 1.5.3), comparison of $I_{r \text{ (operation)}}$ does not require any of the buildings within the pools to share similar functionality. The BECs methodology does not impose any form of handicap which would limit the pool of buildings that may be employed for comparison. For example, the effectiveness of energy-use performance in a hospital in a hot climate could be compared with a school in a cooler climate. The significant point is that the building's ranking is based purely on its ability to achieve the energy saving potential of that particular building (based on climatic conditions, building use, etc.).

This hierarchical ranking of the project would be of interest to all project participants. It would also be of interest to projects outside of the original project. For instance, if a project is highlighted as having high values of $I_{r \text{ (operation)}}$, then the BECs methodology provides an enabling methodology for supporting effective operational strategies.



3.2.2 Performance Effectiveness Ratio

Operational values of the I_r (operation) are not the final chapter in the BECs methodology. Energy efficient design solutions must be *complemented* by effective operational-strategies (CIBSE 1999). High-performance indoor environmental conditions outlined in Section 2.2.5 are only possible through effective facilities management (Clements-Croome 2000). Studies suggest that energy savings of between 15 and 40% could be made in commercial buildings through closer monitoring and supervision of energy usage and related data (Herzog and LaVine 1992; Claridge et al. 1994). As a result, there are still likely to be considerable opportunities for improving and optimising the performance of the mechanical solution by employing effective management strategies (Canbay et al. 2004).

Efficient management and control schemes aid the reduction of energy-use by maintaining process variables (temperature, humidity, flow-rate, etc.) at their assigned set points (Turner 2004). However, HVAC processes are inherently dynamic. Characteristics can change on a seasonal basis due to energy performance being subjected to many heterogeneous agents. The effects of changing building control and operation are difficult to predict.

Strategy selection for the management of the HVAC system in the building is an important part of environmental operation (Turner 2004). During the winter season, it is important to consider the benefits from solar effects. However the occupants must be protected from the cold. Additionally, during the summer months, an adequate *cooling strategy* must be operated effectively. A building's environmental control strategy should determine both the time and rate controls and therefore, disparate control modes that respond to disparate climatic conditions (Santamouris 2004). Finally, it should reflect the building use and the requirements of the occupants.

A building owner will not be satisfied with a facility manager undertaking new forms of operation for the building without being able to predict the consequences (especially if this means poor thermal comfort conditions in the building spaces).

This highlights the need for an effectiveness ratio which acts an *operational target* for the FM which couples the assessment of effective energy-use with adequate levels of thermal comfort within the spaces in the building. The ratio offered by the BECs methodology to



fulfil this requirement is termed the Performance Effectiveness Ratio (P_r) and its sole purpose is to provide continuous operations feedback to the FM team. These values provide a quantitative target for effective operational performance in the building (Figure 3-7).

Building Life Cycle Phase	Function	Performance Communication to each Project Stakeholder				
		Client	Design Team	Facility Manager	Occupants	Community Knowledge base
Operation	• Operational Performance Target	✓	✓	✓	✓	✓

Figure 3-7- The function of P_r and the building stakeholders who may comprehend the result

3.2.2.1 Operational Management Optimisation

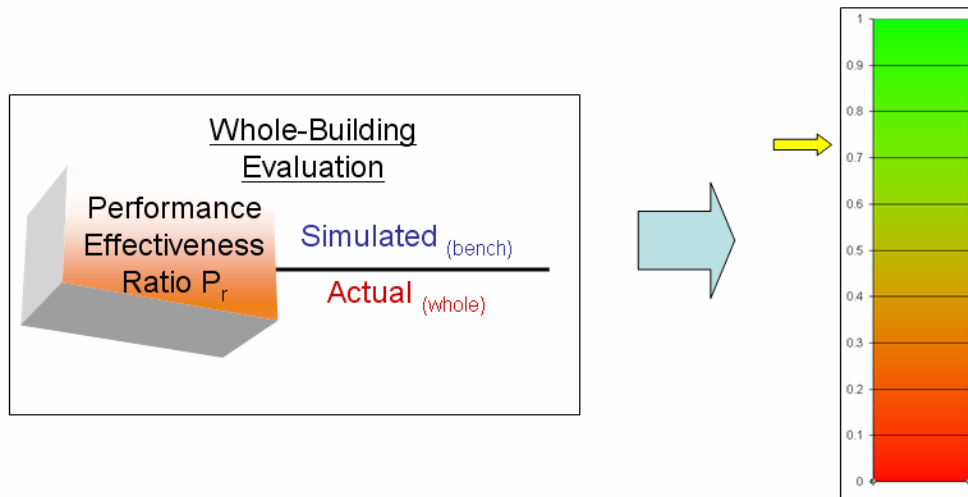
Calculation P_r values employs two data warehouses (Equation 3-5). Data representing actual performance are leveraged from the BMS (Section 2.3.3.1.1). The fully calibrated energy simulation model is employed to provide data to represent the ‘ideal’ (Section 2.3.3.2.2.4).

Once again, values of P_r range from 0 to 1 with higher values highlighting superior energy efficient operations practices. Any values greater than ‘1’ highlight operational performance beyond the design plans.

When operational strategies are evaluated and current energy performance is highlighted as ‘poor’ (low values of P_r values close to 0), the FM, specialist energy consultant and the client may evaluate the management of the building in order to achieve higher levels of operational performance.



SOURCE	Simulated _(bench) ::	Energy-use data leveraged from a fully calibrated system-dependent simulation model. Data represents the levels of energy required to mechanical service the building given optimum management schemes
	Actual _(whole) ::	Energy-use data leveraged from the BMS. These data represent the actual energy utilised in managing the building



Equation 3-5 –Calculation method for whole-building values of P_r

3.2.2.2 Moving Operational Performance beyond Design Intent

The effectiveness of alternative control strategy analyses and Energy Conservation Measures (ECMs) for improving operational performance can be assessed in the system model without disrupting real-life occupants (Clarke 2001). It is envisaged that this analysis will be carried out by the specialised energy consultant. Updated values are retrieved from a model.

Alternative ECMs may be tested in this model (see 2.3.3.2.2.5) in order to leverage a level of performance superior to the current performance in the building. Accordingly, they may be communicated to the FM who may adopt them within the building. These optimal sets of values (displaying reduced energy requirements while maintaining adequate levels of thermal comfort) are employed as the new ‘ideal’ when calculating values of P_r . The energy management team may now begin to work towards achieving this new target of effective operational performance. New sets of P_r are calculated as described in Equation 3-5.



If the effectiveness of energy-use within the building is improved through new operational strategies, an updated value of I_r (operational) may be calculated (by updating the ‘actual’ performance in the ratio calculation). This update provides the design team with new feedback so that these efficient operational strategy principles may be employed in successive projects. These principles increase the design team’s knowledge-base of environmental design. However, if values of I_r (operational) are employed for the ranking of the project, these values of I_r may be improved in order to improve the hierarchical position in the set of buildings (Section 3.2.1.4.3).

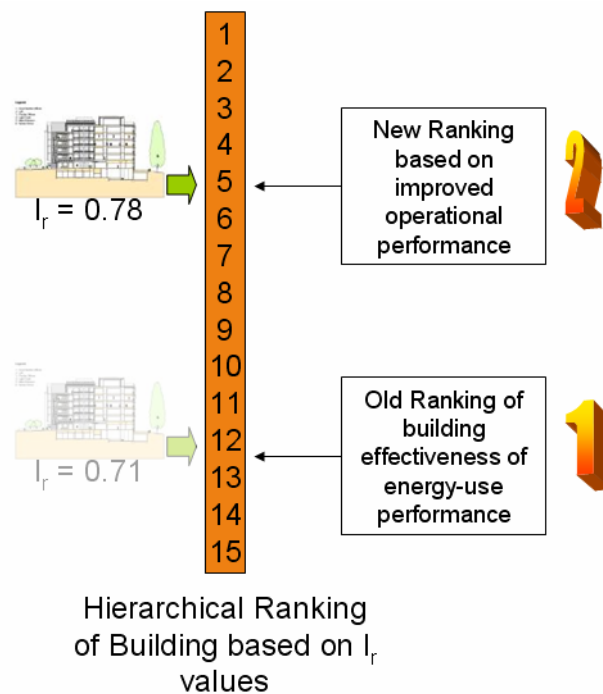


Figure 3-8 – Improved the ranking of the building’s energy-use performance as a result of engaging in performance improvement targeting

3.2.3 Building Life Cycle Communication

There are many experiences of communication ‘breakdowns’ at all stages of the BLC (Section 1.3.1). Critical design information falls into fragmented ‘middle grounds’ between the client and the design team (Kiviniemi 2006) and again between the building design and operations teams (Selkowitz et al. 1996). The practice of designing, constructing and operating buildings to suit indoor and outdoor climate conditions is



complex and involves many disparate specialist teams. Although virtually every element and process in a typical building project has evolved and become even more complex over time, the building information management methods that ought to support and integrate these activities have largely remained stagnant and outdated (Kiviniemi 2006). Typically, the FM team often have few enabling tools at their disposal to aid the operation of a building. However, current enabling tools usually come in the form of:

- 1) volumes of O&Ms; and
- 2) a log of performance history.

Paper-based specifications and graphical drawings with text annotations are still the *de facto* standard within the industry (O'Sullivan et al. 2004). Typically, a building is handed over with several volumes of O&Ms. However, text-based documents are filled with technical information which are not user-friendly and *rarely* consulted by facility managers (Jones and Davies 2003). Vast quantities of information pertaining to the intent behind design decisions made by project individuals are altered or lost due to poor documentation (Selkowitz et al. 1996).

The lack of communication acts as a form of dual-highway of ineffective practice; building operators receive inadequate instructions for the operation of the building and similarly, design teams receive no feedback on the adequacy and effectiveness of their solutions.

The UK has made a significant effort to improve operational performance by introducing mandatory logbooks in new and refurbished buildings from 2002 onwards (ODPM 2005). This logbook is intended to provide the building owner (or occupier) with HVAC details, controls, methods of maintenance & operation and other pertinent data related to energy consumption. This is a significant step in the right direction as monitoring and targeting of installations are vital for energy management.

However, this research considers that neither of these enabling tools enables effective communication between the design team and the operation team throughout the BLC. The environmental design philosophy is not available post-design and there is a complete *absence* of design feedback. The result of this lack of communication is that building



operators receive little instruction on how the building is set up and how to run it effectively.

An effective example of life-cycle management of a dynamic product can be seen in the life cycle of an automobile. When an automobile is bought, the owner is furnished with a reasonably simple user manual and somewhere to log maintenance history. Additionally, the owner is unlikely to be an expert in the dynamic processes in the automobile and, accordingly, the automobile is serviced by a mechanic (an expert on the dynamic parts of the automobile) on a regular basis.

It is vital that this fundamental practice is mirrored in the building stock. The operational team must receive adequate instruction on the operation of the building and must engage a specialised energy consultant for ongoing assessment of the operational performance of the building. Without such an environment, the building owner is often left with a facility dependant on excessively high levels of energy-use and inadequate levels of thermal comfort for the occupants (Selkowitz et al. 1996).

Within the industry, there are ongoing efforts into increasing the information transfer and communication between project teams include the IDM methodology (Espedokken 2006) and the COBIE methodology (Kiviniemi 2006). The IDM methodology aims to provide an enabling framework to support different user groups (among the pool of project stakeholder) and improve cross communication. The COBIE methodology aims to support the gathering of information during the construction phase in order to ensure optimal operation (as per the client's original requirement).

The BECS methodology assumes a similar life-cycle perspective on the data that must be retained throughout the BLC. Due to the large increase in data required for regular performance assessment, an enabling data warehouse must be employed which facilitates access to all project stakeholders. Accordingly, a standard is required to facilitate the exchange of ideas and the impact of design or operation alteration. The BECs methodology considers the use of tracking values of I_r and P_r in a controlled environment similar to the one discussed in 'Performance Metric Tracking' (Section 1.5.6) as the most effective means of communicating dynamic HVAC process information.



3.2.3.1 Capturing Design Intent in the BECs Methodology

The ability to augment a knowledge-base of sustainable design is lost if each facility fails to archive the details of the decision making process and resulting operational performance. Accordingly, there is significant value in keeping a log of all decision making and the associated data that influenced these choices (Figure 3-3 and Figure 3-7). Once sets of I_r and P_r are calculated, it is vital that they are stored and maintained (Morrissey et al. 2005a). The BECs methodology employs software to facilitate adequate archiving of BECs values throughout the BLC in the BIM (Section 3.2.3.2) for ease of referral by all project stakeholders. The archiving of BECs values (and pointers to the associated simulation models which leverage the calculation data) performs two vital functions:

- 1) a record of the design intent by the HVAC design team is captured for referral at any downstream stage; and
- 2) the use of simulation models implicitly communicate the *design philosophy* (vital instructions for effective building-operation can be referenced throughout the BLC (Hitchcock et al. 1998)).

Accordingly, a life-cycle perspective for the management of building information is facilitated. Such an environment provides the environment necessary for improving the efficiency of society's building stock (Selkowitz et al. 1996; Hitchcock et al. 1998; BLIS 2000).

The linchpin of any effective performance history archive is the placement and coupling of the qualitative performance objectives and quantitative performance metrics:

- 1) the performance objective stores a qualitative statement which communicates the design intent for the relevant building element (e.g. the rationale behind the selection of a particular HVAC system); and
- 2) the performance metric stores a reference to the quantitative data (values of I_r and P_r values).



In order to address this pivotal issue for the proposed assessment framework, performance indicators are organised hierarchically following the *tree metaphor* utilised in many computer programming environments today. A tree metaphor aids communication for non-specialised project stakeholders due to its simplicity of interpretation. A neural network (Warwick et al. 1995; Fine 1999) could be utilised to support further interaction and increase the breath of analysis, however this is considered as future work for the BECs methodology.

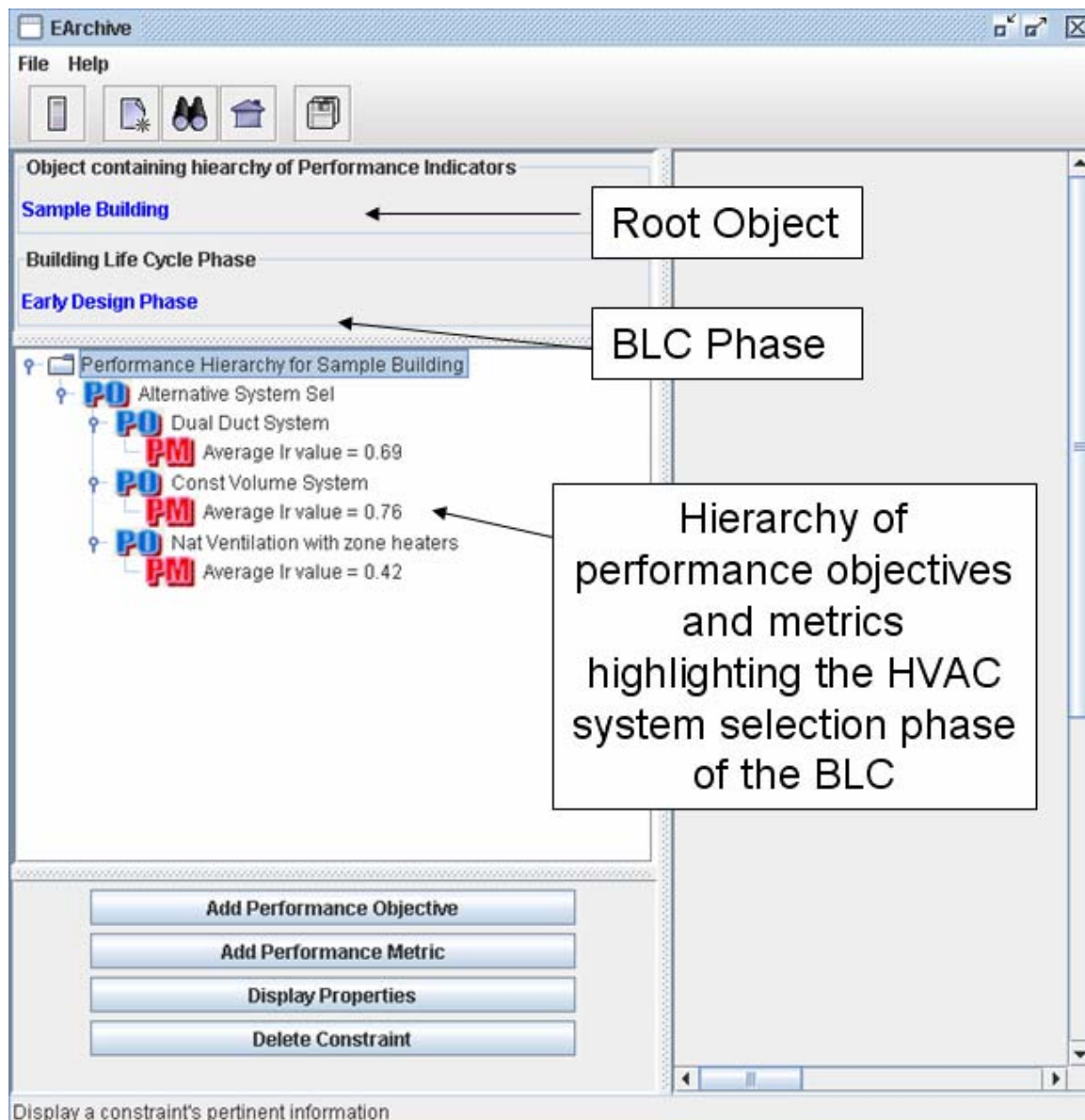


Figure 3-9 – Sample hierarchy in EArchive (Section 4.5) of performance objectives and metrics during the early design phase



The placement of the performance objectives and metrics on this ‘tree’ is referred to within the industry as ‘programming’. The root of the tree is the building project itself. The branches are made up of sub-performance objectives and the leaf nodes are specific performance metrics providing quantitative feedback for the root component (Figure 3-9).

The goal of programming is to define a set of quantitative targets (values of I_r and P_r) to accurately define the desired performance of the building. This process of programming is accomplished through discussions between the all project participants so that any decisions made in the design or retrofit process are considered by all project stakeholders. Programming is facilitated in iterative steps:

- 1) project stakeholders jointly decide on a set of applicable performance objectives;
- 2) program (break down) the objectives to a hierarchy that is self explanatory and easily navigable;
- 3) associate a performance metric (BECs values) to explicitly represent each base performance objective using quantitative data.

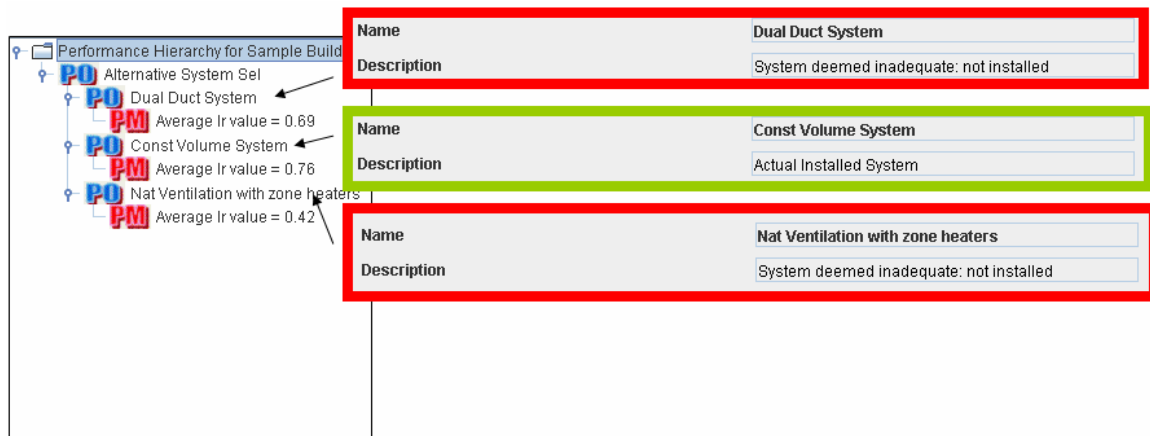


Figure 3-10- Additional information which may be stored in a BIM documenting the decision making process during the early design phases of the BLC

In the same way that computer programmers use comments to *explain* the reasoning behind thousands of lines of code, it is imperative to adequately comment on the



reasoning behind the *myriad* of design and operation decisions. During the programming of the performance objective and metrics, it is possible to input additional information pertaining to specific design decisions for future reference and evaluation (Figure 3-10).

3.2.3.2 Storage of BECs values in the BIM

By keeping a record of BECs values and the selection process in a central location that is accessible to all project teams, similar issues may be addressed in successive buildings. As discussed in the previous section, a hierarchy of performance objectives and metrics provides a vehicle for continually recording and assessing building energy-use performance (BECs values) throughout the operational phase of the building. Accordingly, BECs values are stored in the BIM for ease of referral by all project members (Section 2.3.5.2).

This integrated environment, underpinned by a neutral data file format (Section 2.3.5.3), enables cross-discipline evaluation of BECs values (e.g. architect, client, building occupants, facility manger, etc.).

EArchive is a tool for directly interfacing with a BIM underpinned by the IFC2x2 schema (Section 2.3.5.3). This tool provides enabling software for ‘programming’ the hierarchy of performance objectives and metrics directly into the BIM description of the building throughout the BLC (Section 4.5).

This environment, encapsulating the building’s static and dynamic entities of performance evaluation, presents a feedback and feed-forward highway of information:

- 1) it is envisaged that such an environment will improve the understanding of the building over the entire BLC and augment a greater knowledge-base for project stakeholders pertaining to maximum energy performance design;
- 2) by educating everyone involved in the design process, an increase in energy efficiency of the building stock is not an unrealistic goal; and
- 3) by publishing this information (operational values of I_r), clients can evaluate the effectiveness of the teams employed to maximise the performance of the building throughout the BLC.



The process of programming (see previous section) should be undertaken at the earliest possible stage of the BLC. This documents the rationale behind design decisions and points to the correct operation of the building's systems.

3.2.4 BECs Ratios: Point of Responsibility

Co-ordinating and communicating the impact of various tangible and intangible elements on energy-use is a difficult and skilled process. An important question, which must be addressed, is “who is responsible for the maintenance of BECs’ values as the project moves forward through its iterative phases?” This research points to the procurement of a specialised energy consultant. A project life-cycle consultative role by a specialised energy consultant would have a largely beneficial impact on the historically fragmented environment that exists within the industry. This person would have several skills and be highly knowledgeable in:

- 1) the dynamic parts of the building; and
- 2) the ICT environment required to maintain these elements at peak efficiency.

Accordingly, the client obtains a single point of reference for acquiring an environmentally and financially sustainable building. This thesis argues that without this single point of responsibility, no augmentation of knowledge would be made. Every addition to the society's urban development would continue to act as a ‘prototype’, offering no feedback to the design community and no follow-through of this knowledge-base into the next addition to the building stock.

It is vital that this project stakeholder is engaged from the earliest phase of the BLC. Design teams, clients and facility managers can greatly benefit by *early procurement* and *retention* of this specialised energy consultant throughout the BLC. This will ensure buildings created, maintained and refurbished bring benefits to both clients and society at large through mitigated energy dependence. If the client relays his requirements early to the energy consultant through BECs as the enabling framework, then the project team would be able to translate these issues into:



- 1) solid methods (processes explained during the I_r and P_r calculation phases);
- 2) clear performance targets (target values of I_r and P_r); and
- 3) high quality products (values of I_r (operational))

Additionally, it is vital to retain the services of the specialised energy consultant as the facility matures during building operation. The operational costs for a facility tend to be far greater than those incurred during the design process (Clements-Croome 2004). Clements-Croome elaborates on this point by pointing out that the level of expertise employed during the design stages tends to be far greater than the levels of expertise employed for ‘running’ a building. A tendency to appoint maintenance and operations staff based on lowest price exists. The financial savings possible due to effective facility operation inevitably points to the added value of clients retaining a single and continuous *point of responsibility*.

3.3 Key concepts of the methodology: revisited

As mentioned earlier, the BECs methodology is underpinned by five key concepts. The metaphor of an arch bridge was employed to depict the relationship between the methodology and the concepts (Figure 3-2). Accordingly, it is important to discuss the semantics of how the BECs methodology is underpinned but also supports these concepts in order to delineate their importance to the framework.

3.3.1 Performance-based assessment

The BECs methodology is underpinned by a performance-based assessment environment (suggested in Section 1.4.7 by CIB). The methodology does not deviate from the guiding principle whereby all assessments evaluate the ends rather than the means. The holistic effects from specific design decisions are all assessed so that no adverse penalties are imposed on the building performance without due consideration from project stakeholders. Accordingly, BECs values normalise the different priorities, technologies, building regulations and requirements that exist in various regions and countries as suggested in the Green Building Challenge (Section 1.4.6).



3.3.2 Performance metric tracking

The BECs methodology is developed on top of much of the work carried out by O'Sullivan et al (Hitchcock et al. 1998; O'Sullivan et al. 2004). Sets of performance metrics are tracked to aid evaluation of the building energy-use performance (Section 1.4.7). When employing the BECs methodology, values of I_r and P_r are tracked and stored at distinct stages of the BLC in order to create a view of performance at that point. This increases the information available to project stakeholders so that they may make more informed design decisions.

3.3.3 Communication

High levels of operational performance throughout the BLC will only be enjoyed by projects that adopt integrated design and operations practices founded on a collaborative approach where common goals are set out for everyone to work to (Best and Valence 1999). Increased levels of communication throughout the BLC are vital for successful downstream performance. Within the collaborative environment project teams, as well as project individuals, require:

- 1) good communication skills;
- 2) a willingness to change old processes (with a realisation that the old ways are not necessarily the best);
- 3) an ability to learn new skills;
- 4) an ability to share a holistic vision of sustainability throughout the BLC;
- 5) a mutual respect for the knowledge and experience of other specialist teams;
- 6) imagination and flexibility; and
- 7) an interest in occupants' needs.

The ease of interpretation of information from a particular specialist field is a crucial factor for the engagement of communication. A willingness to communicate must be facilitated with an enabling language of communication. The BECs methodology supports communication by providing a universally understandable yardstick of performance capable of interpretation by all project stakeholders due to the simplicity of



representation. This is significant, as it facilitates consultation with all project stakeholders (e.g. communication with the QS during the system selection phases to assess the capital costs of the systems).

As seen in Figure 3-2, the concept of *communication* acts as the keystone for the BECs methodology. The significant issue here is increased communication with all project stakeholders with particular emphasis on the client. After all, he is the project stakeholder who will be burdened with any maintenance costs and he is already supporting the design costs. BECs values offer a language of communication with the client throughout the entire BLC so that the client can ensure that a philosophy of energy efficient design, at the project's conceptual stages remains uncorrupted philosophies of design and operation throughout the BLC.

3.3.4 Application throughout the BLC

High levels of operational performance are only possible through early consideration of the impacts made by the myriad of heterogeneous agents which affect energy performance. Additionally, this practice must be progressed as the facility ages. At each stage of the BLC, the BECs methodology provides a universally understandable yardstick of energy-use performance. Additionally, the methodology employs tools and technologies that are inherently flexible. As a result, any alterations that may be made over the course of the BLC may be assessed and quantified using the methodology.

3.3.5 Interoperable software environment

The BECs methodology provides an enabling language for increased communication between project stakeholders. However, it is vital that this increased communication is mirrored by an integration of the software environment employed by these project stakeholders. Accordingly, the BECs methodology is underpinned by a neutral data file format (as discussed in Section 2.3.5.3). All data transfer is facilitated through interfacing with this interoperable central BIM (Section 2.3.5.2).



3.4 Industrial Operation Benefits

One of the main aims of the new EU directive (Section 1.4.1) is to promote the introduction of cost effective strategies in new and existing buildings. A large pool of buildings within the EU (approximately 160 million (Dix 2003)) will have to display an asset and a performance rating for their building. Additionally, the EU has established an EU-wide emissions trading scheme under Directive 2003/87/EC (EU 2003a), which has been in effect in all EU member states since 1st January 2005. The EU Directive applies to all combustion installations across the EU with a rated thermal input exceeding 20 MW as well as a range of other activities such as steel and cement production, paper, ceramics and glass manufacturing.

Research has highlighted that by integrating an assessment methodology with performance-based building codes (similar to the EPBD), building owners will benefit from a single repository of information (Lee and Yik 2002). As a result, there is significant scope for the introduction of a methodology such as BECs in the current EU building industry climate.

3.4.1 Cost

In the 21st century, a building must ‘work’ for its intended use. But it should also do so in a cost effective manner. Reports from one economic journal discuss the point that a business’ productivity is increasingly being scrutinised by evaluating ratios which compare productivity with bulk energy-use (Economist 2006). Inefficient buildings, and therefore high money wasters, are not *appreciated* as adequate core products. For many businesses, being the proprietor of a ‘green’ building is becoming an important issue (Section 3.4.2).

When adopting any new framework as a driver for a project, the cost benefits are the key issue. The additional cost (both in terms of finance and time) of employing the BECs methodology must be given due consideration by all project stakeholders. However, it is considered that this will be offset by the increased productivity (as discussed in 2.2.5) and increased financial savings due to efficient operational energy-use (BECs values couple the internal comfort with energy usage).



For those industries involved in emissions trading (Section 3.4), the increase in energy-use performance due to the BECs methodology has additional benefits. These operators receive an allocation of CO₂ emission allowances for a set period. If actual emissions exceed their stipulated allowance, the operator must purchase additional allowances from other operators within the EU. However, if emissions are lower than the allocation, the operator can sell the excess allowances to those with a shortfall. Operators must accumulate sufficient allowances to cover annual emissions, or else face a financial penalty payable to the EU (EU 2003a).

Promotion of an energy efficient building stock is a realistic goal given the current favourable climate to sustainability (Hui 2003). Additionally, the impending energy labelling of a building, highlighting its energy performance throughout the BLC, will create increased transparency within the industry. Those not taking responsibility for operational performance will be highlighted. It will not be in the interest of businesses to be perceived as acting in an unsustainable manner. Therefore, the energy efficiency of facilities will become a core issue for a business in the future.

3.4.2 A Business's Public Rapport

An increase in operational energy-use efficiency will help the facility achieve a superior performance rating from the impending EU legislation labelling scheme (Section 1.4.1). Many businesses consider their public perception a significant issue. The business may wish to be viewed as a 'responsible trade company' in the public domain. As a result, it is vital that several core assets belonging to the business, such as the building stock, are perceived as energy efficient. They risk poor public perception if the buildings are labelled with poor performance ratings by the EPBD (discussed in Section 1.4.1). This may give rise to serious adoption of the BECs methodology.

3.5 Chapter Summary

The BECs methodology provides universally appreciable yardsticks for measurement of building energy-use performance. These yardsticks are termed I_r and P_r and they translate complex definitions of sustainability for energy efficiency and depict simple views underpinned by 'industry-standard' building appraisal tools. I_r and P_r values are



calculated through comparison of predicted/measured energy-use with ideal building energy-use. Accordingly, all values range from 0 to 1 with higher values denoting superior performance.

The methodology builds on the strengths of existing assessment tools, frameworks and concepts:

- 1) it is a performance-based assessment of holistic energy-use;
- 2) it facilitates tracking of sets of energy-use performance metrics;
- 3) it provides continuous design and operations feedback to project stakeholders throughout the BLC;
- 4) the methodology is supported in an interoperable environment (where tools and technologies are employed to best fit the projects needs);
- 5) increased communication between all project stakeholders including the client is facilitated by the methodology's universally understandable outputs.

The BECs methodology facilitates evaluations of design decisions and operations strategies made at every stage of the BLC. Seated in an interoperable environment, BECs make use of energy simulation tools and BMS metering facilitating parametric analysis of design decisions. Armed with this knowledge-base, project stakeholders now have the power to make informed decisions throughout the BLC.

It is envisaged that effective use of BECs would promote a building stock that are designed to achieve their energy saving potentials. Employing a methodology should give an environmental design a set of *quantitative* and *tangible* targets necessary to overcome any resistance to efficiency curbing measures during the construction and operation processes. It is envisaged that the BECs methodology will:

- 1) provide a platform for best practice and pragmatic improvement of environmental design and operation;
- 2) provide an enabling methodology for decision support throughout the BLC;
- 3) qualify and quantify the energy performance of the building throughout the BLC;



- 4) provide quantitative feedback on the building's predicted/actual performance at each stage of the BLC;
- 5) raise the awareness of everyone involved in the project (including the AEC&FM community, clients and occupants) to the implicit energy saving potential of the building;
- 6) aid the provision of a robust environment that manages adequate thermal comfort conditions for building occupants in order to increase productive output;
- 7) promote smart facilities and operation-management which employ performance-based solutions;
- 8) facilitate downstream evaluation of a project's design decisions in order to augment the knowledge-base within the industry;
- 9) support the EU labelling and emissions-trading schemes;
- 10) be flexible and adaptable enabling change over time in a cost effective manner;
and
- 11) educate and enlighten professionals (AEC&FM), clients and academics as to the holistic performance of new ideas associated with a sustainable urban built environment.





Chapter 4

Software Tools Employed by the BECs Methodology

The BECs methodology requires the use of an integrated suite of software tools to support a building energy-use performance assessment. Initially, a CAD software tool may be employed in order to expedite the configuration of the building's form in the whole building energy simulation tool. All data related to the building must be configured in a whole building energy simulation tool and, finally, an enabling tool for archiving performance related data. This chapter discusses the enabling tools which facilitate the employment of the BECs methodology.

“Any intelligent fool can make things bigger and more complex... It takes a touch of genius - and a lot of courage to move in the opposite direction.”

- Albert Einstein



4.1 Introduction

In order to address the key issue of building information loss, data are increasingly being stored in a BIM (Section 2.3.5.2). Popular CAD vendors such as Autodesk, Graphisoft, Nemetschek and Bentley have all developed their own proprietary data models for these 3-D descriptions of the geometric building form (Autodesk 2002; Bentley 2003; Graphisoft 2003). However, non-proprietary integrated product models – facilitating access to a wide variety of different software tools – may be employed for many additional beneficial and distinct purposes downstream of this early phase. Such an integrated environment can lead to increased savings for all projects stakeholders (Gallaher et al. 2004; Neuberg et al. 2004).

A BIM underpinned by a neutral data file format was chosen as the storage environment for all building information pertinent to the BECs methodology (building form, average values of I_r , average values of P_r , pointers to external data warehouses, etc.). Such an environment has two key benefits:

- 1) By adopting a *non-proprietary integrated environment*, users can employ the tools that best match their requirements and respond to the needs of project participants within a specific phase of the project life cycle (e.g. disparate energy simulation tools, etc.);
- 2) The environmental design and operation issues may be individually optimised within different applications to respond to the specific needs of the building, but they are linked by a shared information structure facilitating external evaluation of design decisions and intent (e.g. external evaluation of energy-use performance).

Ongoing development efforts aimed at the development of a non-proprietary product model for the integration of a suite of tools in order to facilitate the exchange of building information data include:

- 1) Industry Foundation Classes – IFCs (IAI 1995); and



- 2) Green Building XML – gbXML (gbXML 2006).

Additionally, significant effort is currently being undertaken in the US to develop a national BIM standard (NIBS 2006).

For the purposes of this research, the BECs methodology employs IFC-based BIMs, (Sections 2.3.5.3 and 3.3.5). The following subsections discuss several IFC2x2 compliant tools² which may be utilised in implementing a BECs assessment in a real life scenario.

4.2 CAD Software Tool

The process of generating information for the BIM begins with a geometric description of the building's form. Several architectural CAD tools may be employed at this stage to export a description of the building in the IFC2x2 format³ including (Bazjanac et al .2006):

- 1) Autodesk's Revit 8/8.1'
- 2) Graphisoft's ArchiCAD 8/8.1/9;
- 3) Nemetschek's Allplan FT 17.



Figure 4-1 – Exporting a building generated in ArchiCAD as an IFC file

² It should be noted that the latest release of the IFC schema is IFC2x3 IAI (2006). buildingSMART. IFC2x Edition 3, final documentation available at http://www.iai-international.org/Model/R2x3_final/index.htm, however all development work was based on the previous release of the schema (IFC2x2).

³ There are many other applications capable of interfacing with other versions of the IFC schema including Bentley's Microstation, etc.



The process begins with an object orientated description in the software tools own proprietary format and subsequent translation into the IFC2x2 non-proprietary environment. Certain descriptive techniques are employed at this stage to ensure an adequate description of geometry for the energy simulation model (Bazjanac 2001). Once this step has been undertaken, it may be imported to a variety of downstream IFC2x2 compliant applications.

4.3 Geometric Model Validation

Solibri Model CheckerTM (SMC) is a software solution for validating the geometric and spatial integrity of BIMs by applying *rules* to the object-based entities (Solibri 2005). It also has additional functionality outside the scope of this research.

By applying a Constraint Set Manager (CSM) for managing and configuring sets of constraints, SMC provides automated ‘design spell-checking’ to a building model. For the purposes of configuring an input configuration for a geometric form in an energy simulation tool, space boundaries and wall objects’ global placement are assessed. Accordingly, these errors come under the headings of:

- 1) a pre-check of the geometric model (CAD components);
- 2) interference checking; and
- 3) space checking.

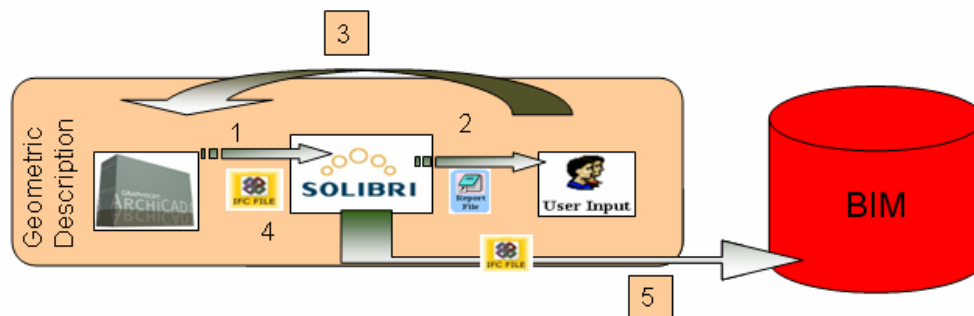


Figure 4-2 – Diagram displaying the iterative step involved in validating the geometry

As can be seen in Figure 4-2, there are five systematic steps which must be undertaken when validating the geometric instantiation within the BIM:



1. A *geometric instantiation* of the building's form is exported from an IFC2x2 compliant CAD tool (e.g. ArchiCAD, Allplan, Revit);
2. The CSM (within Solibri) checks for errors in the IFC file and reports these to the user (in text format);
3. After consulting the text output from Solibri, the user addresses any inadequate descriptions made in the original CAD instantiation of the building with regard to the downstream energy simulation model;
4. This revised version of the model is exported from the CAD tool in the IFC2x2 format and re-evaluated in SMC;
5. If no further errors are encountered, a validated geometric instantiation of a BIM is leveraged from the process. Otherwise repeat steps 2, 3 and 4.

4.4 Simulation Model

Energy simulation tools are one of the most important tools at the disposal of design engineers due their predictive capabilities (Augenbroe 2002) and they are vital to the generation of BECs values (Section 2.3.3.2).

EnergyPlus is the only directly IFC2x2-compliant energy simulation tool in North America (Bazjanac et al. 2006). EnergyPlus' 'whole-building' energy performance simulations are based on the dynamic effects from the many distinct building elements that have a bearing on energy performance. These elements include building envelope; building configuration; heating; cooling; natural and electrical lighting; solar; natural and mechanical ventilation; internal air flow; building occupancy; use and operation; its local generation of energy; and most other effects that affect building energy performance (US-DOE 2005). Simulations of building performance can be broken down into design days or any given period of time. It combines the best features of its predecessors (BLAST and DOE-2) and it can be linked to external software tools such as SPARK or COMIS if further resolution is required.

Another significant benefit associated with the use of a whole building energy simulation model containing walls, windows, spaces, HVAC, lighting and lighting equipment is its



capability to capture *design philosophy* (Hitchcock et al. 1998) (Section 4.5). For example, the final simulation model generated in the detail design stages documents the solution and strategy employed by the design team to achieve the stated performance objectives (Section 2.3.3.2.2.2).

The ability of an energy simulation tool to interface with the information stored within a data-rich BIM provides a platform for the *seamless* exchange of data among different applications providing the ideal platform for quick and responsive solutions (Bazjanac 2003). Bazjanac elaborates on this by considering the many savings possible through sufficient utilisation of interoperable environments resulting in increased *quality* in simulation. These benefits lend themselves to a methodology that promotes innovation in design through the ease of communication between building design tools and holistic building energy-use appraisal.

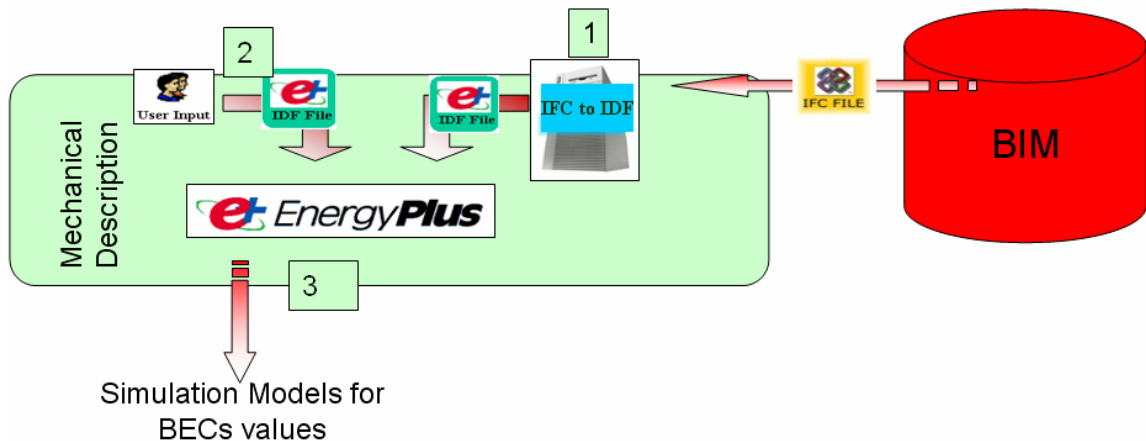


Figure 4-3 – Systematic generation of a HVAC description in EnergyPlus using an existing geometric description in a BIM and a subsequent instantiation of HVAC information in the same BIM

Figure 4-3 outlines the iterative steps involved in undertaking a whole-building simulation of the building using EnergyPlus:

1. The description of the building's form is imported from the BIM and translated into EnergyPlus' input format (IDF) (Section 4.4.1).
2. A description of all components and control parameters is manually configured for the model (Section 4.4.2).



3. Analysis of the simulation models is performed in order to leverage data for calculation of BECs values.

4.4.1 IFCtoIDF interface for EnergyPlus

Traditionally, users of HVAC simulation tools manually configure the input file (IDF) for EnergyPlus when defining the building's geometric form. This is an extremely laborious and error prone task (Mourshed et al. 2003). However, as discussed previously, EnergyPlus is IFC2x2 compliant and geometry may be directly imported from the IFC data model in order to expedite this configuration task.

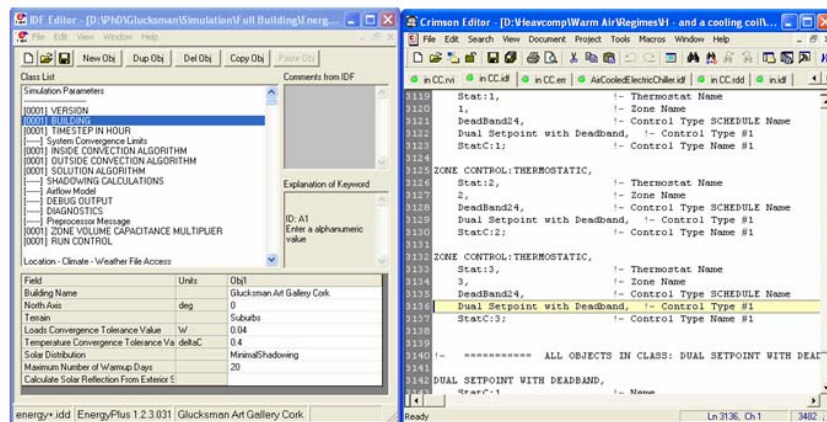
The IFC data model is capable of containing more definitions of data in more detail than any single simulation engine will require. For instance, the resolution in geometry detail is far greater than required by EnergyPlus. Accordingly, all geometric descriptions that are imported to EnergyPlus must be simplified.

During the simplification process, two middleware tools strive to generate the rectangular geometry definitions required by EnergyPlus. Geometric data is imported into BSPro (which simplifies and reorganises the geometric information) (Karola et al. 2002). This file is subsequently utilised by the IFCtoIDF tool which manipulates the information with respect to EnergyPlus's proprietary representation of geometric information (IDF).

Unfortunately, this translation of geometric information between IFC and IDF does have several limitations. The largest issue is an inability to resolve complicated space boundaries. Accordingly, additional manual alteration of the resultant IDF file is required by the user. However, it is considered that this issue will be resolved in the near future.

4.4.2 Manual input of pertinent building operation data

Currently, the input file for EnergyPlus must be configured manually by employing peripheral configuration tools. Figure 4-4 depicts two software tools which may be employed to aid this configuration process: (a) depicts the 'IDF Editor' which is a GUI currently bundled with EnergyPlus and (b) depicts an example of a plain keyboard text editor (Crimson-Editor 2005). These tools facilitate the input of occupancy loads; performance curves and schedules; control parameters; and all pertinent HVAC elements.



(a)

(b)

Figure 4-4 – Alternative software tools employed for configuring simulation models in EnergyPlus (a) IDF Editor or (b) Text Editor

It is possible to store specific descriptions of HVAC configurations (e.g. Variable Air Volume (VAV) units, boiler circuits, etc.) which may be used in several projects. Templates of these definitions can be copied and pasted into a myriad of input files expediting the process of configuring the specific IDs for leveraging data for calculation of BECs values.

Adequate description of the building, and its HVAC systems, is vital to the success of the BECs assessment of energy performance. The energy simulation model is only as effective as the configured input.

All room conditioning and air/fluid movements within a HVAC system are defined in terms of loops (which are broken up into demand-side and supply-side), branches, components and nodes. System process variables may be assigned to components, however all geometric effects on energy performance are accounted for in their thermal parameter values.

All HVAC plant elements ultimately service a room/space which is termed a ‘zone’. These zones may be assigned parameters such as room use, load profiles, geometric entities, operating regimes etc. However, the geometric location of HVAC plant elements is *not* accounted for in EnergyPlus.



Any modifications made to the building design during design/construction/operation *must* be documented in the BIM. New simulation runs provide updated benchmarks or expectations of building performance. This provides an up-to-date repository of the *design* and *operation* philosophy which is maintained throughout the BLC.

4.5 Archiving BECs values in the BIM

In any building project, proficient storage of *qualitative* and *quantitative* sets of information during the design and operation stages is critical and must be considered (Beller et al. 2001). Accordingly, the tracking of performance metrics throughout the BLC is one of the key concepts underpinning the BECs methodology (as discussed in Section 3.3.2). As a result, proficient storage of performance objectives and performance metrics – that describe the intent behind the myriad of design and operations decisions – is one of the key processes undertaken when employing BECs.

Figure 4-5 – Example of the input form for a Performance Objective in EArchive

The methodology employs EArchive (an ‘IFC2x2-compliant’ software tool developed over the course of the research to aid the documentation of design throughout the BLC (Morrissey 2005)). This tool facilitates the archiving of information in an IFC-based BIM by directly interfacing with the IFC file. This process is considered to be pivotal to the success of BECs for contributing to the knowledge-base within the industry (Section 3.2.3).

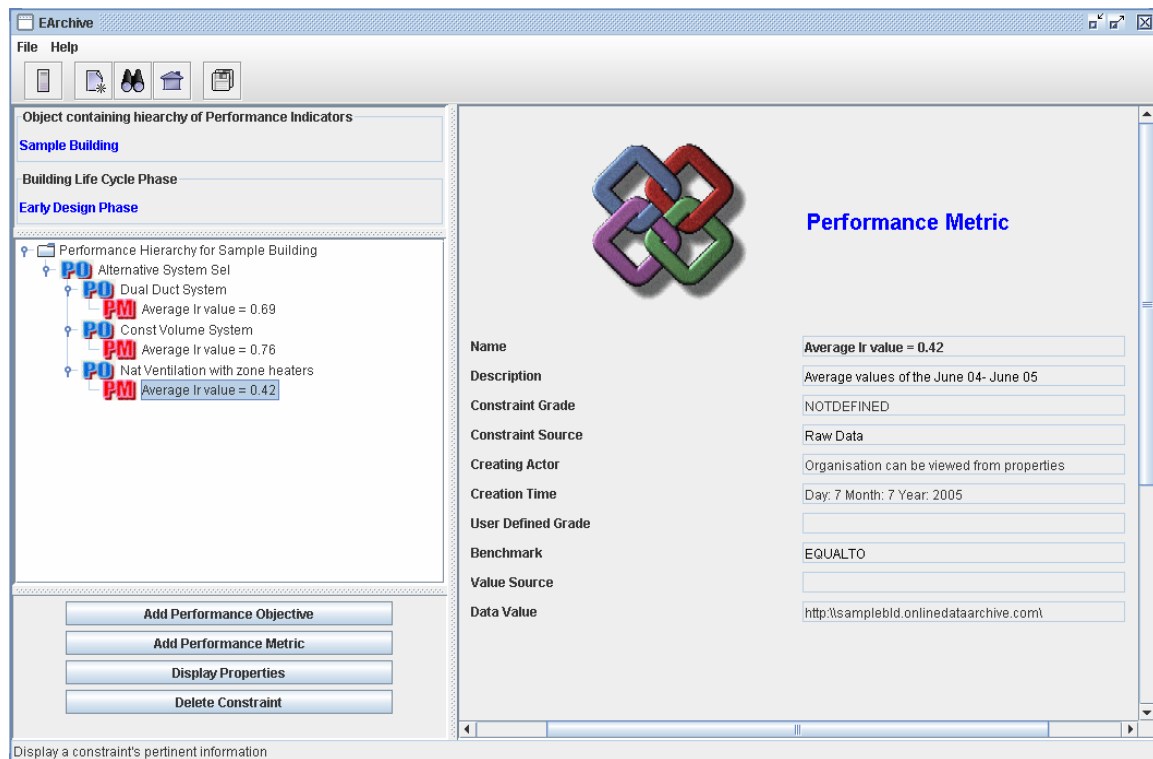


Figure 4-6 – Sample output from EArchive displaying information that may be stored and the location of the raw data in the ‘Data Value’ section

The principle behind the development of the tool is to assist in documenting the design intent and to ensure an enabling repository for documentation of the design process is provided. This information is generated through the programming of a hierarchical series of performance objectives and performance metrics (Section 3.2.3.2). These are initially generated during the early design stages and may be revised, deleted or added to as the project progresses. As a result, the rationale behind the myriad of design decisions made as a project evolves is archived and documented for subsequent retrieval.

Creating a ‘tree-view’ of nested performance objectives and metrics is referred to as programming (Section 3.2.3.2). This aims to capture the *design intent* (as seen in Figure 3-9). Qualitative performance objectives indicate specific objectives (or steps) required to generate specific quantitative targets (values of I_r and P_r). These targets, termed ‘performance metrics’ by the industry, act as the leaf nodes within the hierarchical tree-view. The base performance metrics contain average BECs values and pointers to the locations of the data (for future evaluation purposes).

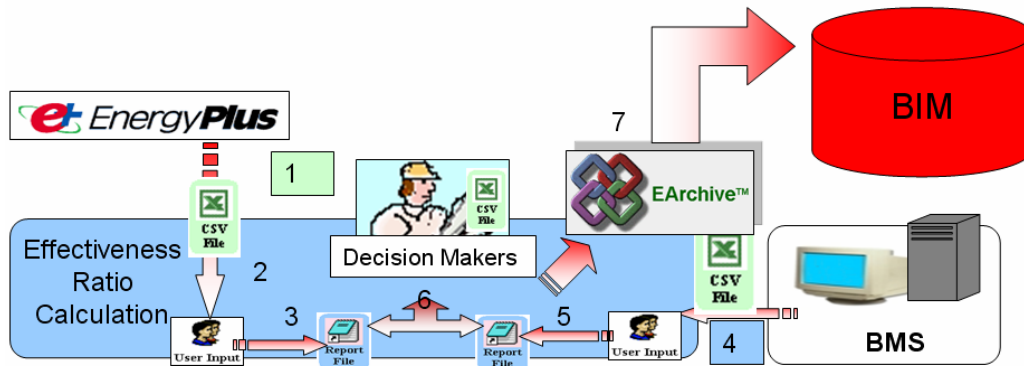


Figure 4-7 – High level overview of the tools employed the generation process and the subsequent storage of a hierarchy of performance indicators in the BIM

Figure 4-7 outlines the environment required for development of BECs values which are archived in the BIM. Within Figure 4-7, the numbers concern specific iterative steps that are undertaken post simulation. Steps 1 through to 6 pertain to the calculation phases for BECs I_r and P_r values (Sections 3.2.1 and 3.2.2 respectively). Step 7 relates to the programming of the actual hierarchy itself. The design intent is related at this step through the programming of a series of performance objectives and metrics. The quantitative data associated with the qualification of I_r and P_r values may be referenced from this hierarchy through the storage of a location (this location may be an internet address or a folder on a network (WAN/LAN)) (Figure 4-6).

Ultimately, EArchive furnishes a building project with a permanent store of information facilitating the querying of any (1) design strategy; (2) building component selection and (3) intent, by downstream evaluation teams. Additionally it aids communication throughout the BLC by making the entire decision-making process more transparent by associating tangible quantitative yardsticks of performance (BECs values) with specific design decisions.

4.6 Chapter Summary

The BECs methodology requires an enabling set of tools and an associated data storage platform for proficient support, evaluation and documentation of design decisions by project stakeholders. BECs values aid the design decision process. However the industry requires a means to evaluate these steps downstream of the process. Accordingly, all data



is stored in a central BIM which provides a platform for an integrated suite of tools. Such an integrated environment complements BECs values which provide an enabling language for increased communication throughout the BLC.

The BECs methodology employs an IFC-based BIM for storage of all data pertinent to the BECs assessment of building energy-use performance. Accordingly, several IFC-compliant tools are required for the programmatic approach taken by this framework:

- 1) a CAD tool for the creation of the geometric form for the building;
- 2) a whole building energy simulation tool for a full environmental description of the building; and
- 3) an enabling tool for archiving the rationale behind the design and the operation of the building by pointing to specific BECs values.







Chapter 5

Design of Experiment

This chapter illustrates a trial implementation of the BECs methodology's assessment of a real building: UCC's Glucksman Art Gallery. Each of the functionalities offered by the methodology is explored by testing the robustness and effectiveness of the methodology when applied to this building.

“By three methods we may learn wisdom: First, by reflection, which is noblest; second, by imitation, which is easiest; and third by experience, which is the bitterest.”

--Confucius



5.1 Objectives

The primary objective of this chapter is to delineate the various messages conveyed by the methodology to support the decision making process engaged in by the stakeholders in achieving energy efficiency through building design and management. Accordingly, the functions encapsulated in the BECs values first introduced in Chapter 3 are revisited. In order to gain an insight into the possible messages that may be presented by BECs values, this chapter aims to evaluate the value of:

- 1) I_r (early design) (in aiding all project stakeholders select an energy efficient HVAC system to mechanically service the building);
- 2) I_r (detail design) (in aiding the HVAC design team select specific components for the HVAC system);
- 3) I_r (detail design) (in predicting downstream operational performance);
- 4) I_r (detail design) (for use as an ‘Insurance of Design’ for the design team (pre-construction));
- 5) I_r (detail design) (in minimising the impact of cost-cutting exercises which are often synonymous with a project design phrases);
- 6) I_r (commissioning) (in predicting future operational performance);
- 7) I_r (commissioning) (as an ‘Insurance of Installation’ for the building and installation project stakeholders);
- 8) I_r (operation) as an objective evaluation of actual building performance;
- 9) I_r (operation) (as a feedback tool for all stakeholders involved in the design phase);
- 10) I_r (operation) (as an objective project evaluation tool); and
- 11) P_r (as an enabling quantitative yardstick for measurement of operational performance and its ability to aid the FM in achieving the energy saving potential of the building as intended by the design team).

Several distinct data sources and technologies must be employed in order to generate the BECs values described above. These data warehouses and analysis tools are delineated for each calculation (Appendix B). Additionally, hierarchies of performance objectives



and performance metrics are programmed as prescribed in Section 3.2.3.2. These hierarchies highlight the value of documenting BECs values throughout the BLC.

5.2 Glucksman Art Gallery: An Introduction

The Glucksman Art Gallery (Appendix A) was employed as the pilot implementation of the BECs methodology. This facility houses art exhibition spaces which are open to the public throughout the week. The building itself consists of seven split-level floors with four exhibition areas, several multifunction rooms, lecture facilities, a café/restaurant and a basement gallery store. The building was procured and opened by University College Cork in late 2004 in order to showcase its own modern art collections as well as travelling and special exhibitions.

Art galleries by their very nature demand a highly controlled internal environment for the safe keeping of the art collections. Anne Fahey, in her reference book titled *Collections Management* (Fahey 1994), presents detailed text to develop standards for collections management. It highlights the significance of building *type* and *condition* as vital discriminating factors. It pointed to the fact that poor conditions endanger collections housed within the spaces.

The client (UCC) stipulated a desire for an art gallery designed with a minimal environmental impact. As a result, it was vital that any HVAC solution would maximise energy efficiency and *yet* guarantee the safe provision of the internal environment. Accordingly the design of the building was driven by a policy to mitigate the building's environmental impact while maintaining strict internal environmental conditions. This presents challenges for employing energy simulation software during the calculation phases of I_r and P_r .

Most importantly for the BECs methodology is the presence of a BMS system. Temperatures, humidity levels, air and water flows, and other values pertinent to the safe provision of an internal environment are automatically logged by the BMS system. The Glucksman Art Gallery's BMS is bundled with a Graphical User Interface (GUI) front end. FMs may investigate process parameters by interfacing with this software. Additionally, archives of historical process and environmental data are accessible from this tool.



5.3 A BLC Evaluation of Building Energy-use Performance

In order to carryout a full BLC evaluation of the building energy-use performance for the Glucksman Art Gallery, several enabling tools and technologies were selected to provide the required data and storage facilities:

- 1) EnergyPlus is employed as the whole building energy simulation tool (Section 4.4);
- 2) the Glucksman Art Gallery has a fully installed BMS (Section 5.2); and
- 3) an IFC-based BIM is employed for all data reference and storage (Section 4.2).

During the course of the experiment, numerous limitations were placed on the resolution of the Glucksman Art Gallery's performance assessment. These limitations led to several simplifying assumptions. The actions taken as these issues were encountered are described below:

- 1) In general, the Glucksman Art Gallery's BMS has a lower density of sensoring of HVAC system process variables than is required for the BECs methodology's assessment of BLC performance. This is a common issue in the industry. Unfortunately, this lack of operational performance data means that the methodology may not be applied to the particular building. However, the two spaces housing the gallery's travelling exhibits, serviced by a single AHU (termed AHU3) , are adequately sensed.
- 2) The main spaces within the building are generally serviced by an air loop and a convective system (e.g. radiator, underfloor heating, etc.). This poses a significant problem for EnergyPlus as the software does not facilitate the autosizing of multiple systems (required for early design selection and detailed design component selection)⁴. However, AHU3 is the only internal environment

⁴ Many of these whole building energy simulation tools have many shortcomings (including an inability to accurately mirror the performance of the actual building under assessment). The data leveraged from these tools suffices as a best approximate of operational energy efficiency in the building. Additionally, the



tempering device in the building and EnergyPlus facilitates a full autosizing of this unit. Accordingly, all assessment of building energy-use performance is constrained to the zones serviced by this AHU. These zones are referred to as the Media Room and the Close Control Gallery.

- 3) EnergyPlus is currently unable to adequately control the humidification process for typical AHUs that were under assessment for the Glucksman Art Gallery⁵. All BECs evaluation of building energy-use performance has been purposely limited to the month of July. It is considered that this month adequately represents the dehumidification loads experienced by the building's systems.
- 4) In the absence of an up-to-date weather file for the Cork area, the Kilkenny (a nearby location with a similar climate) weather file was employed for all simulation models. Such weather files are referred to as Typical Meteorological Year (TMY) (US-DOE 2005) weather data for the local area. These weather data are a representative of the climatological features of the site over a typical year⁶.
- 5) All models are configured with identical boundary conditions (occupancy profile, lighting, infiltration, etc.) (Appendix A and B). This ensures that no handicapping of the performance evaluation may occur across distinct BLC phases (Section 3.2.1.4.3).

The remainder of this section discusses the evaluation of the zones serviced by AHU3 at each phase of the BLC. A full BLC evaluation of the unit may be engaged as this research was furnished with access to 'as-built' and O&M documentation.

capabilities of these tools are envisaged to mature and ultimately deliver more accurate data as they evolve into more robust tools.

⁵ EnergyPlus was unable to maintain tight control of the moisture content in the main AHU during the humidification season (winter months). This leads to the cooling coil being needlessly engaged. Accordingly, all downstream dehumidification and heating loads are overly inflated and would result in an unfair evaluation of the system.

⁶ It should be noted TMY files suffice during the pre-operation phases of the BLC, however, it is preferable to use actual locally measured climate data (in order to leverage accurate evaluations of $I_{r(\text{operation})}$ and P_r).



5.3.1 Utilising I_r values

In this section, the performance of AHU3 in the Glucksman Art Gallery is evaluated at each phase of the BLC utilising BECs values. The I_r values provide direct feedback to the design team (Section 3.2.1).

5.3.1.1 HVAC System Selection

Two alternative schemes are assessed for consideration by calculation of their benchmark energy use (Section 6.6B.5.3):

- 1) a constant volume system; and
- 2) a VAV system

The BECs methodology facilitates a form of regression analysis during the alternative system selection process. All boundary conditions are identical and constrained during the alternative assessment (e.g. space loads, lighting loads, climatic conditions, etc.). This enables the BECs methodology to make a superior qualification of performance for different systems. Both systems contain identical system layouts. However one system contains a constant volume configuration while the other system has the ability to moderate the flow of air based on space requirements. Through analysis of output from simulation models, the average volumetric flow rate of air through a VAV system ($0.34\text{m}^3/\text{s}$) is half the flow rate of air through the constant volume system ($0.66\text{m}^3/\text{s}$). This leads to improved efficiency in the cooling and heating circuits which is appreciable by all project stakeholders through I_r values⁷.

Several simplifications of the model were required due to EnergyPlus' inability to adequately maintain Relative Humidity (RH) conditions which has led to an oversimplified benchmark model (Section 6.6B.5.2). Accordingly, the values of the 'ideal' in the calculation are considered to be extremely low and impractical. However,

⁷ It is important to note that AHU3 is required to be fully operational throughout the day (for the safe provision of the artefacts stored within the space). Accordingly, average values of I_r are taken over a full 24-hour operation throughout the month of July.



for the purposes of demonstrating the BECs methodology's philosophy, the data sets do enable a portrayal of system performance.

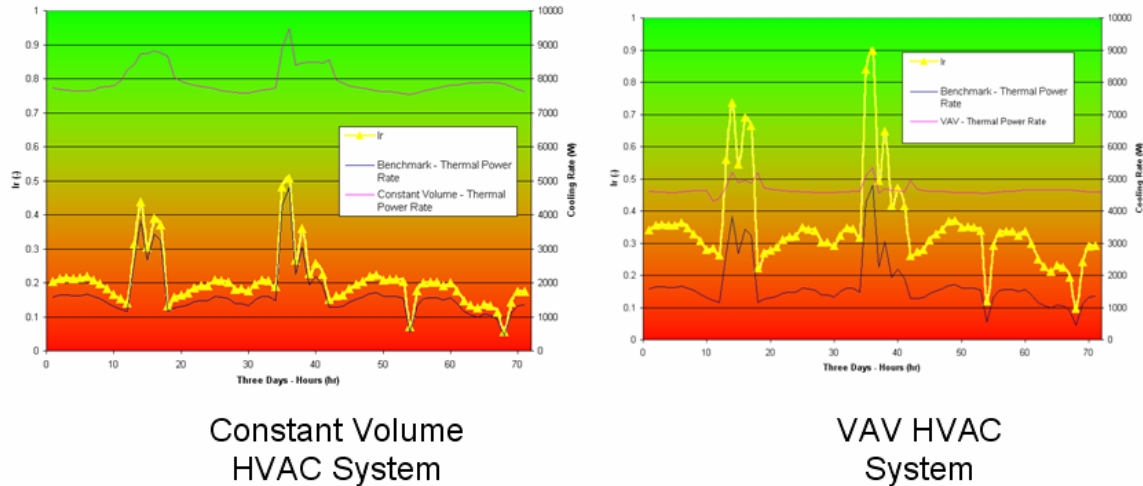


Figure 5-1 – The hourly distribution of cooling coil I_r values for the alternative systems over a three day period in July

Figure 5-1 depicts the distribution of values of I_r for the cooling coils for the alternative systems. Both graphs depict identical benchmark cooling thermal power rates of the energy-use. However the VAV system displays significantly lower energy-use requirements (as much as one third) over the same time-period.

The effects of these reduced levels of energy-use are difficult to conceive by a non-expert. However, values of I_r enable the system selection process as they provide a universally understandable yardstick of performance measurement. The VAV system can clearly be seen to exhibit higher values of I_r throughout the three days. These I_r values are mirrored throughout the month of July and average I_r values for the VAV system's cooling coil are noticeably higher (Figure 5-2). This graph highlights a potential performance of 0.45 for the VAV system compared to a potential performance of 0.28 for the Constant Volume System. Armed with the yardstick of performance measurement, experts and non-experts are better placed to make informed decisions for alternative system selection.

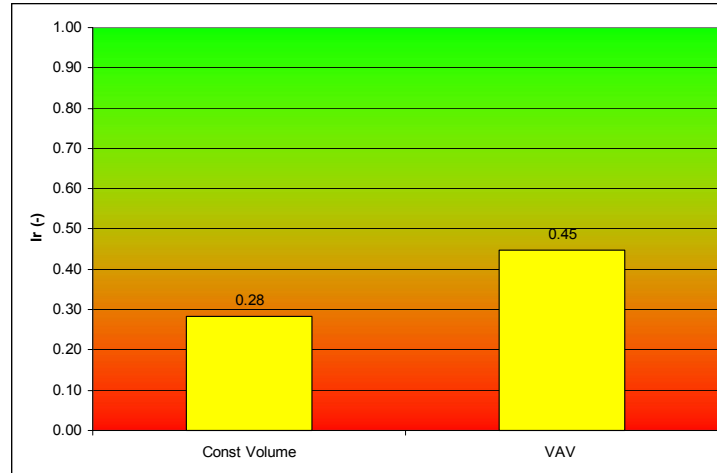


Figure 5-2 – July average values of I_r for each of the alternative systems

Average values for the whole system and individual components must be calculated and assessed alongside each other. Figure 5-3 highlights the column graph which aids system selection during these early design phases. In this graph, the VAV system is clearly highlighted as the more efficient system. Each of the components in the system offer superior performance resulting in a higher average I_r values to total performance (as highlighted in Figure 5-2). These values enable the design team to make an objective system selection decision during the early phases in design.

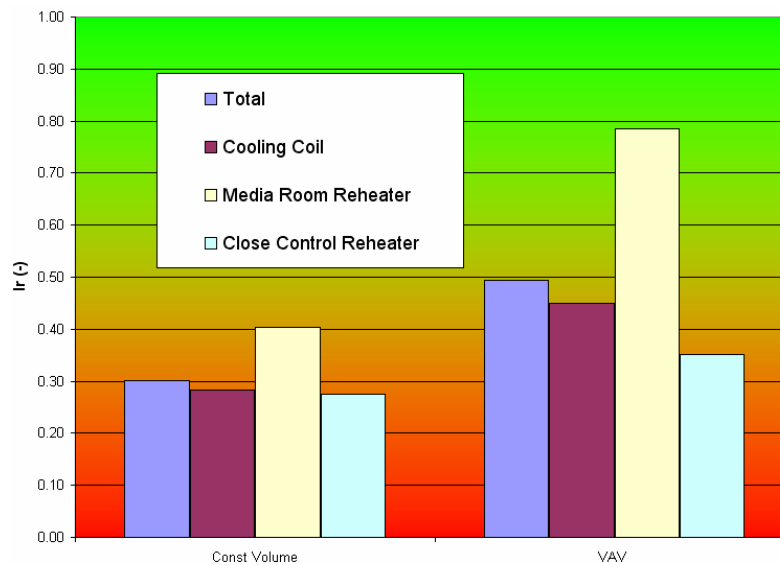


Figure 5-3 – Column graph delineating the holistic and component performance using values of I_r



5.3.1.2 Detailed Design Phase

The use of I_r values for AHU3 during the detailed design phase enables:

- 1) system component selection and evaluation;
- 2) an update in performance prediction;
- 3) an insurance of adequate design for the design team; and
- 4) an enabling tool for cost-cutting impact evaluation.

The data and methods related to the aforementioned processes involved at this stage in the BLC are captured in the BIM through the programming of a hierarchy of performance objectives and metrics for downstream referral and evaluation (Section 5.3.3).

5.3.1.2.1 System Component Selection

During the system component selection process, two distinct I_r values are calculated (Section 3.2.1.2.1):

- 1) I_r – Component: These values assess the effectiveness of the components which may be chosen for the actual system. They are calculated through comparison of the actual component's performance (Section 6.6B.5.6) with the autosized version of that system (Section 6.6B.5.5).
- 2) I_r – Total: These values predict the performance of the system using the selected HVAC components. They are calculated through comparison of thermal power use from the system-dependent configuration (Section 6.6B.5.6) with the system independent (benchmark) configuration (Section 6.6B.5.2).

In order to delineate the performance evaluation process for the HVAC system components selected for AHU3, two scatter graphs are plotted for AHU3's cooling coil over the three day period (Figure 5-4). As can be seen from the 'Component Performance' graph, average $I_{r\text{-component}}$ values highlight the selected component is achieving 60% of the potential efficiency available from this type of component (average



$I_{r\text{-component}}$ values are delineated as 0.6). This corresponds to inferior $I_{r\text{-total}}$ values when the components performance is compared with the benchmark model.

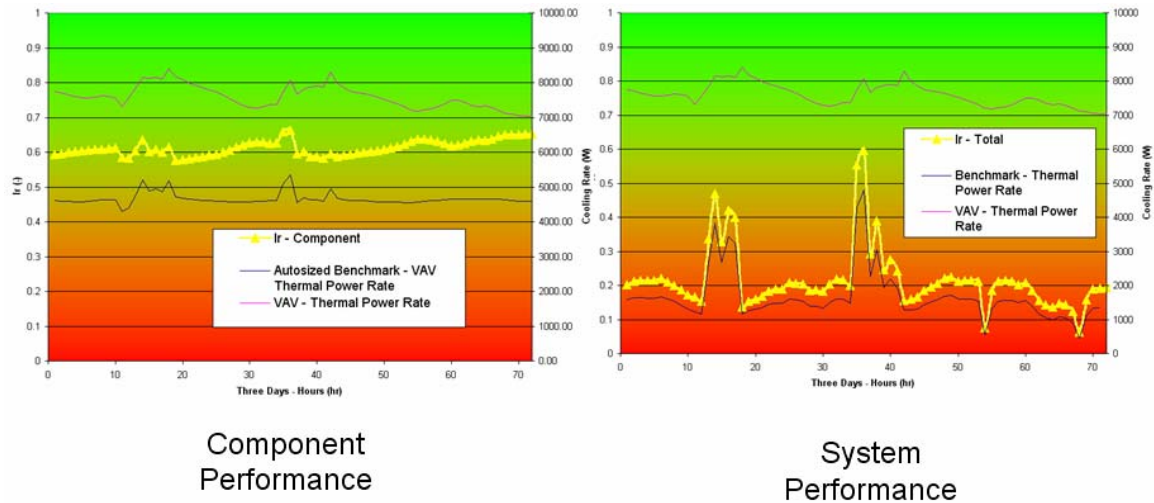


Figure 5-4 – Evaluation of the performance of the actual cooling coil when compared with the ideal system-dependent configuration and in comparison with a system-independent configuration

Figure 5-5 displays the column graph evaluating the performance of each component during the selection process. As can be seen in this graph, the component selection process would *not* be qualified as a success using the BECs methodology. $I_{r\text{-component}}$ values highlight that the selected components are resulting in holistic performance only achieving 62% of the ideal efficiency of a VAV configuration. This is due to inefficiencies in the selected components. This ineffective selection process can clearly be seen to reduce holistic total $I_{r\text{-total}}$ performance from the early design phase to the detailed design phase (values of 0.49 to 0.31 respectively). Accordingly, the components selected for AHU3 have not resulted in the unit achieving its energy saving potential.

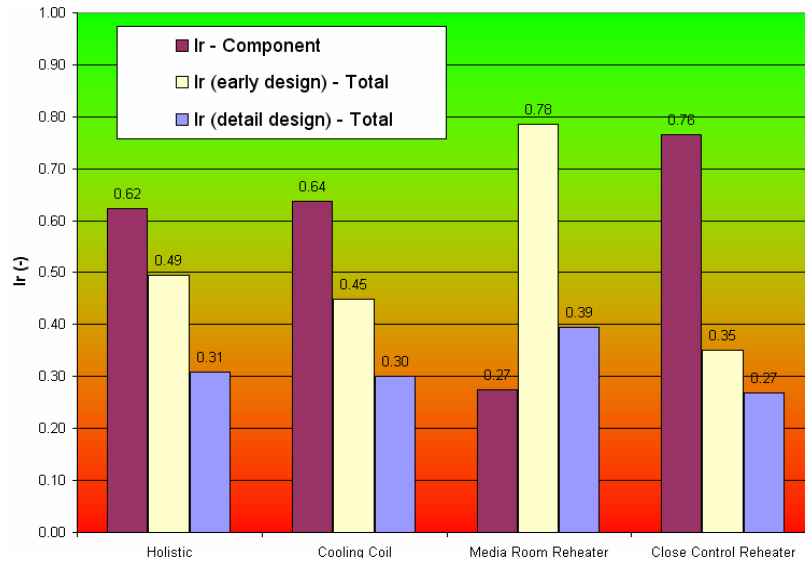


Figure 5-5 – Total and Component I_r (detail design) values for each of AHU3's components along with the holistic performance

5.3.1.2.2 Updated Detailed Design Performance Prediction

Using values of I_r (detail design) the predicted performance of AHU3 may be communicated to experts and non-experts alike (Figure 5-6). Holistic performance of the system using values of I_r is predicted to be 0.31 during the month of July. The performance of the cooling coil, media room reheater and close control reheater are predicted to be 0.3, 0.39 and 0.27 respectively. These values may be employed by HVAC design team as their prediction of operational performance.

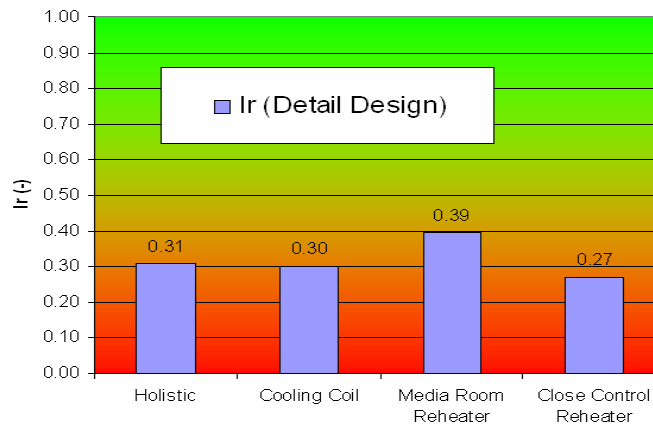


Figure 5-6 – Performance prediction of AHU3 during the detailed design stage using I_r (detail design) values



5.3.1.2.3 Insurance of Design

The values of I_r (detail design) for performance prediction (Figure 5-6) serve as an insurance of design for the HVAC design team. Any operational I_r values lower than 0.31 for AHU3 may be evaluated by assessment of the installation, operation and the data sets influencing the prediction of performance. Accordingly, the client has an enabling yardstick of performance which may be employed to insure all project stakeholders are taking responsibility for high values of energy efficiency in the building.

5.3.1.2.4 Cost-cutting Impact Evaluation

The Media Room and Close Control gallery are not exposed to the external environment. Accordingly, only alterations to system components and the system's boundary conditions may be considered during the cost-cutting impact evaluation. Three hypothetical cost-cutting measures were considered:

- 1) selection of fans with poorer efficiencies;
- 2) increase in space infiltration rates from 1 ach^{-1} to 2 ach^{-1} due to cheaper construction and methods for building air-tightness; and finally
- 3) increase in lighting emitted heat loads (1.5kW) due to the unit's inefficiencies.

The purpose of this process was to highlight the effectiveness of the BECs methodology when selecting the cost-cutting measure which will have the *least* impact on the energy performance of AHU3 (section 3.2.1.2.4). Each of these cost-cutting measures was configured in the detail design energy simulation model (Section 6.6B.5.6). Figure 5-7 highlights the resulting holistic I_r values which were calculated when the benchmark holistic energy-use for AHU3 (Section 6.6B.5.2) was compared with each of data sets from the distinct model configurations.

Holistic I_r values for the three measures highlighted increasing the allowable infiltration rates' from 1 ach^{-1} to 2 ach^{-1} as having the least impact on holistic performance for AHU3 and the best selection for cutting from the building when entertaining a cost-cutting exercise (Figure 5-7).

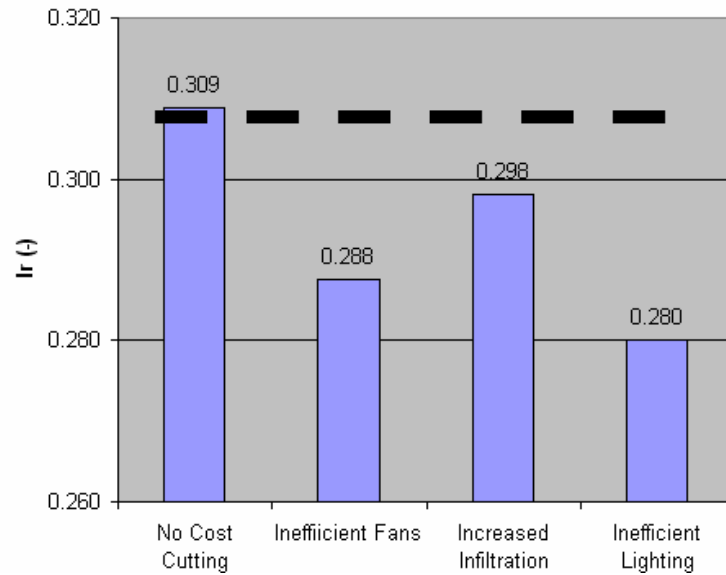


Figure 5-7 – Bar graph highlight the use of I_r values for cost-cutting impact assessment

5.3.1.3 Commissioning Phase

There are two distinct uses of I_r values for AHU3 after the construction and commissioning phases. These include an:

- 1) update in the prediction of operational performance; and
- 2) insurance of proficient construction and installation.

All information related to the processes involved at this stage of the BLC are captured in the BIM through the programming of a hierarchy of performance objectives and metrics for this phase of the BLC (Section 5.3.3).

During the experiment, no new data could be configured in the model. The updated model is a direct copy of the model employed during the detailed design phases. Accordingly, no data sets of I_r are configured for this stage. The predicted performance after this phase in the BLC mirrors the performance prediction from the detailed design phase (Section 5.3.1.2.2).

Hypothetically, if data sets were available and the information was configured in the energy simulation model for this phase of the BLC, new I_r values would be calculated. If I_r values were found to be lower than 0.31 (Figure 5-6), the energy saving potential of the



building would be reduced. Accordingly, the installation and construction teams would be highlighted as not taking due care of the energy efficiency goals for the building and the client would be in a position to suspend payment until some form of mediation was agreed (Section 3.2.1.3.2).

5.3.1.4 Operational Phase

Formal post-occupancy evaluation of the building can be performed by employing the values of I_r (operational). These values provide the design team with an objective evaluation of actual system performance.

As discussed in Section 6.6B.5.11, all evaluation during the operations stage for AHU3 is limited to a three day period.

5.3.1.4.1 Actual Performance Evaluation – Operational Phase

The average value of I_r (operation) for the cooling coil over the three days was calculated to be 0.31 (Figure 5-8). This value is the expected performance of the system from the detailed design stages. However, it should be noted that this figure does not serve as final evaluation of the operational performance due to the limited period of evaluation.

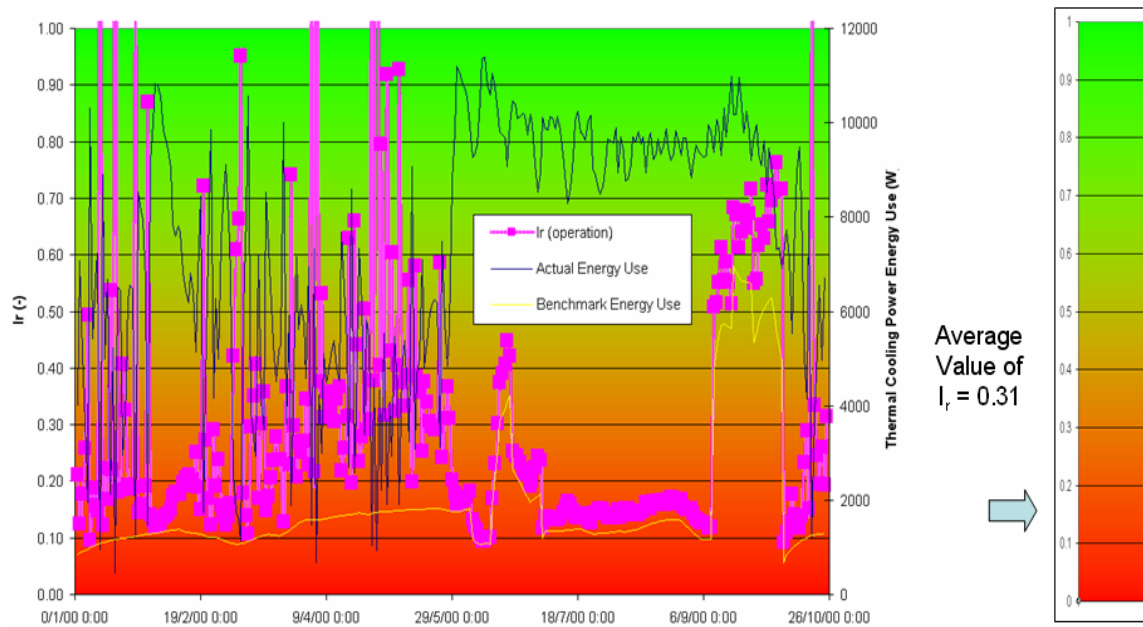


Figure 5-8 – Evaluation of the operational performance using values of I_r over the three period



5.3.1.4.2 Design Feedback – Operational Phase

If AHU3's operational performance was found to be 0.31, then two important messages are conveyed to two distinct project teams:

- 1) the boundary conditions operational practices and operational performance predicted by the design teams were correct; and
- 2) the FM team are achieving the energy saving potential of the HVAC system.

5.3.1.4.3 Project Evaluation – Operational Phase

A large period of operation is required in order to qualify the performance of AHU3. However, if the building's final I_r (operation) was found to be 0.31, then any buildings with higher values of I_r (operation) would be deemed 'more efficient' in a hierarchical ranking system. The opposite is true for buildings with lower values of I_r .

5.3.2 Utilising P_r Values

Energy efficient design solutions must be complemented by effective operational-strategies (CIBSE 1999). In this section, the operational performance of FM team is evaluated using operations data for AHU3 in the Glucksman Art Gallery using values of P_r . Data are supplied from the whole building simulation model and the BMS.

5.3.2.1 Operational Management Optimisation

In order to evaluate the performance of the FM team, it is necessary to compare data displaying actual energy-use (Section 6.6B.5.11) with data acting as the 'ideal' energy-use under normal operation (Section 6.6B.5.10). This comparison is evaluated through assessment of P_r values (Section 3.2.2.1).

Figure 5-9 depicts the calculation of P_r values for AHU3 over a three day period in July. As can be seen, operational management of the building has moved beyond the energy saving potential of the building (the average P_r values is highlight as 1.2). This implies that the actual energy-use within the building is less than the benchmark value for P_r assessment.



Achieving values greater than one is not envisaged to be unusual for P_r . This may be due to the calibrated simulation model's configuration of boundary conditions which may not match the exact conditions experienced by the actual physical components over the time-period (e.g. unexpected low visitations over the time period).

There may be a myriad of additional factors which may result in actual performance moving beyond the benchmark performance during P_r assessment. These factors will be highlighted during future research projects and will enable the benchmark utilised by the methodology to mature.

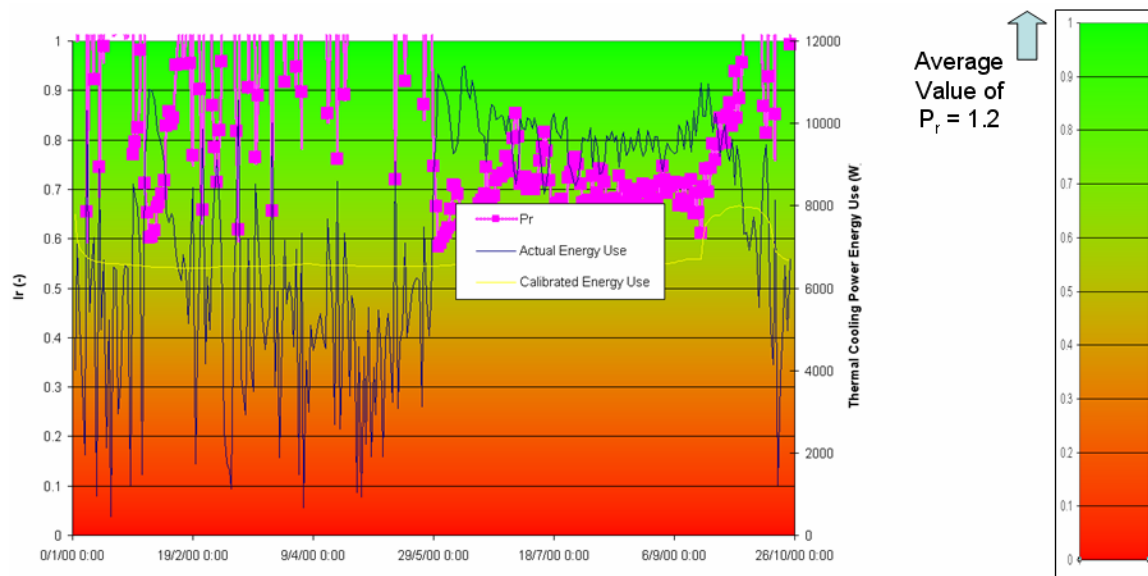


Figure 5-9 – Assessment of operational performance using values of P_r over a three day period in July

5.3.2.2 Moving Operational Performance beyond Design Intent

The simulation model configured to reflect the performance of a VAV system (Section 6.6B.5.10) does not facilitate alteration (if the input file is altered, the tight control of temperature and RH in the spaces is not maintained). Accordingly, no evaluation of alternative ECMs was facilitated. The ability of the BECs methodology to enable the operations team to move the energy saving potential of the unit beyond design intent was not tested.



5.3.3 BIM Archive of Performance Related Data

Ensuring that each addition to the building stock does act as a prototype is one of the guiding principles for the development and implementation of the BECs methodology. Accordingly, in order to make the BECs methodology's processes visible to external evaluation, it is vital to store adequate documentation of the buildings assessment and selection process. A full record of all data and processes involved in the BECs assessment throughout the BLC are stored in an IFC-based BIM for the building (Appendix I). Hierarchies of performance objectives and metrics were programmed to adequately document the procedures for AHU3 efficiency evaluation throughout the BLC (Figure 5-10).

Each performance objective and metric stored in the BIM is facilitated with the option to store additional annotation information which documents the procedures followed when using the BECs values for supporting the decision-making process throughout the BLC by different stakeholders (Figure 5-11).

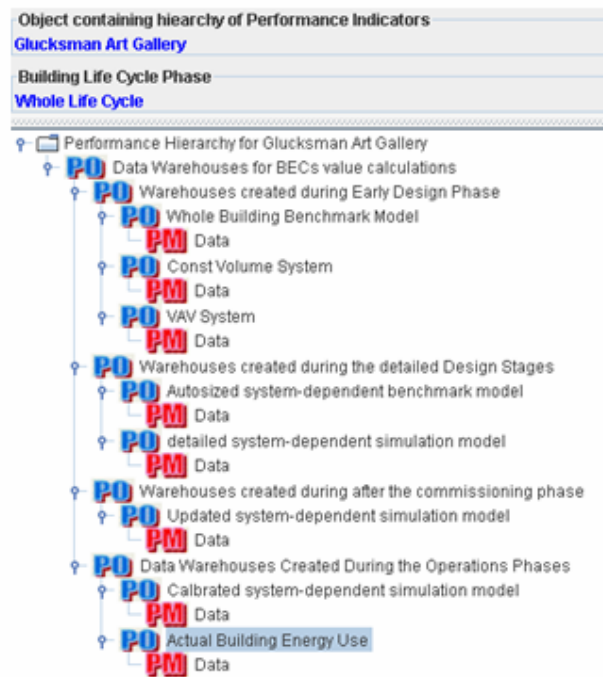


Figure 5-10 – Capturing and referencing the data warehouses employed throughout the BLC for future referral



The continual documentation of the yardsticks (BECs values) throughout the BLC ensures the energy efficiency goals are continually addressed and all project stakeholders are fully engaged in taking responsibility for the impacts that their role may have on the operational efficiency of the building.

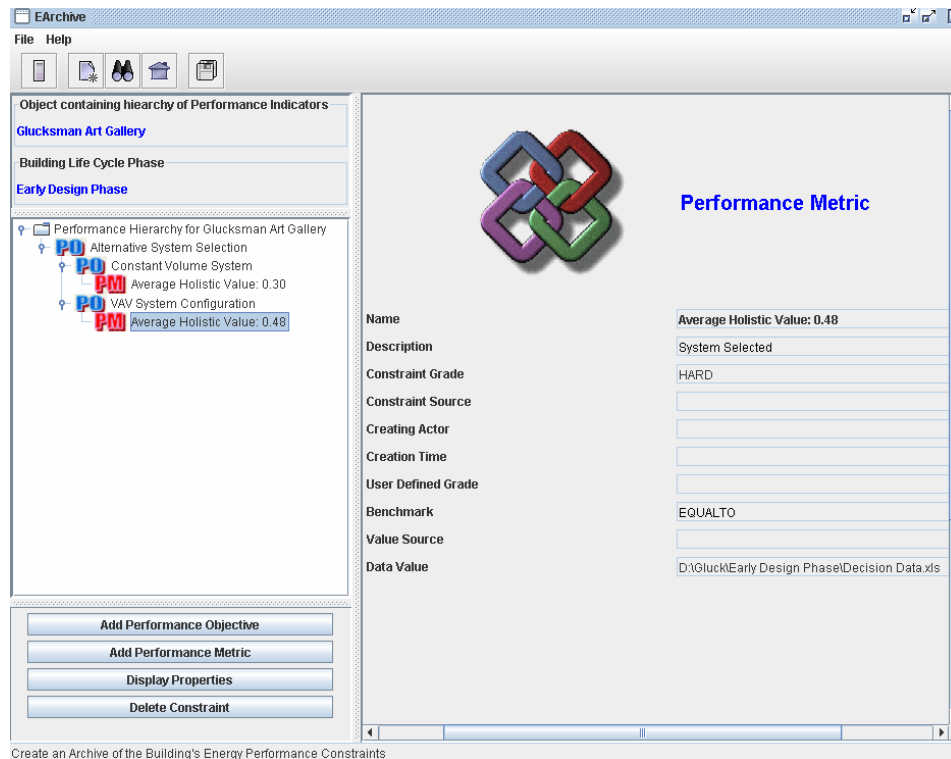


Figure 5-11 – Screenshot from EArchive documenting rationale behind design decisions made during the system selection phase of the BLC

5.4 Chapter Summary

Due to energy simulation limitations and BMS data integrity issues, the investigation of energy performance for the test-case building was limited to a one month period (July) during the pre-operation stages and a three day period during the operational period (mid-July) for a single AHU within the building.

Despite these limitations, an assessment of performance was explored and the potential benefits of the BECs methodology were highlighted in the experiment for various project stakeholders including:



- 1) the design team (for informed decision making throughout the early design phases);
- 2) the client (to ensure energy-efficiency goals for the building are addressed throughout the BLC by making operational energy performance ‘visible’ at every phase of the projects evolution);
- 3) the building’s operation team (by providing a quantitative target for achieving the energy saving potential of the building).

Used throughout the industry, it is envisaged that the building stock will see increased building energy-use efficiency performance and mitigated operational costs due to reduced energy bills.





Chapter 6

Summary and Conclusions

The final chapter discusses the conclusions pertaining to the BECs methodology. A brief summary of the methodology is introduced, along with the research motivation for the proposed framework. The final conclusions made over the course of the research are outlined along with several issues which must be considered for successful adoption of the BECs methodology. The iterative and pragmatic implementation of the methodology is revisited, concluding with future work in the area.

“Concern for man and his fate must always form the chief interest of all technical endeavours. Never forget this in the midst of your diagrams and equations”

- Albert Einstein



6.1 Executive Summary

The building sector is, without doubt, responsible for many of the tangible effects influencing the quality of life and environment. As humans living in the modern world, we spend most of lives indoors. In order for us to maintain our well being, it is vital that the building's internal environment is both comfortable and healthy. However, management of urban developments' internal conditions comes at a cost and it is vital that effective principles of sustainability are adopted by the building industry (Gaterell and McEvoy 2004).

Much can be done to reduce current levels of energy requirements by urban developments. Management of energy-use in buildings is a dynamic and complicated process. Accordingly, it is:

- 1) difficult to visualise and communicate to non-experts;
- 2) subject to the effects of many heterogeneous agents; and
- 3) often perceived as an abstract notion which is difficult to predict and quantify.

This perception is especially true during the early phases of the BLC when the problem is exacerbated by the fact that the earliest design decisions dictate much of the downstream performance (Selkowitz et al. 1996). During the design and construction phases of the BLC, there is no universal means of communicating the operational energy-use effects from the decision-making process. Additionally, there is an absence of an enabling tool to explicitly link design intent with operational performance. This would seem to highlight a requirement for a methodology, which provides a method of linking and communicating the effects of design and operational decisions throughout the BLC.

This thesis addresses the problem by providing an enabling methodology for measuring the efficiency of a building's energy-use performance at each stage of the BLC. The objective behind the BECs methodology was to develop an objective, universally applicable and appreciable *yardstick* of energy performance to enable assessment and quantification. These yardsticks are referred to as BECs values and they provide quantifiable measurements of a building energy-use performance throughout the BLC. It



is envisaged that the *universally understandable nature* of the output will aid round-table decision-making sessions when discussing the holistic effects of specific design/operation decisions.

Despite the relative ease of appreciation (the rating of each specific ratio value is based on a number between zero and one, with higher values denoting superior performance), the generation of BECs values is underpinned by existing industry tools, technologies and environments: an interoperable environment; building energy prediction software; and building energy measurement tools. The interoperable environment links information throughout the iterative stages of the BLC and provides a universally accessible repository of information for all project stakeholders to employ their own specific ‘views’ of the building (Section 2.3.5). The whole building simulation model makes it possible to predict the energy performance of the building under a variety of conditions and also communicates the design philosophy to downstream project stakeholders (Section 2.3.3.2). The building energy measurement tools facilitate a full review/diagnosis of actual building energy-use (Section 2.3.3.1).

Chapter 5 highlighted the potential uses and benefits of employing the BECs methodology for an actual building. Values of I_r and P_r , tracked throughout the BLC provide continuous quantitative performance feedback to the design and operations project stakeholders.

The implementation of the framework on a real building also highlighted the limited capabilities in existing tools and technologies required by the BECs methodology. Ultimately, this research considers that a higher degree of maturity and integrity is required in the functionality provided by these tools.

6.2 Research Motivation

The motivation for introducing and developing the methodology for assessment of building energy-use throughout the BLC stems from several deficiencies and failures within the industry (Section 1.5). There would seem to be a clear absence of enabling toolkits for ‘objective’ assessment of building energy-use without imposing adverse handicaps. The energy performance of a building depends on so many heterogeneous factors which may all result in unfair qualification of the facility’s energy performance.



An additional failing within the industry is the absence of a tool applicable across the entire BLC through the assessment and tracking of performance yardsticks. This key issue is exacerbated by the fragmented nature of the industry whereby islands of expertise and knowledge are rarely pooled (Section 2.2.1). The lack of an enabling language to aid communication results in inefficient building designs, constructions and operations procedures. Additionally, this lack of a common language makes it difficult to augment a greater knowledge-base that would contribute towards a sustainable future building stock. This research considers that any new sustainability methodology that aims to make a beneficial impact on the energy efficiency of the entire building stock requires an environment built on five key concepts (Figure 6-1): performance-based design; tracking of performance data, increased communication and balance between specialist teams (architects, engineers, construction teams, etc.); applicability across the entire BLC; and integrated environments for the pooling of building information.

The key to the methodology's success is considered to be the provision of a yardstick of building energy-use performance which is universally comprehensible by experts and non-experts alike. An educated client provides the linchpin to a sustainable future for the building stock. The proposed methodology aims to aid the design and operation decision-making processes, but most importantly, provide the client with an easily understandable yardstick of building energy-use performance for assessment throughout each stage of the BLC. This increase in knowledge for the client is vital in order to ensure that a sustainable requirement during the building specification stages will not be overlooked as the project matures into the operations stage of the BLC.

6.3 The BECs Methodology: Discussion

An energy-use assessment of a building is not an easy undertaking. There are many varied factors that impact on the operational energy-use of a building (e.g. space use, occupancy profiles, climatic conditions, building form, shading, etc.). As a result, an assessment of the building through the comparison of bulk energy-use with 'like' buildings may often be misleading to the project design team (and the client) (Section 1.5.3). This research considers that no serviceable impact can be made on the future of



society's building stock without a clear determination and visualisation of environmental design impact.

Undertaking a BECs assessment offers an independent evaluation of building performance at each stage of the iterative BLC by comparing a building's actual energy-use with an *ideal version of itself*. It encapsulates a combination of existing tools, technologies and environments in order to augment a superior knowledge-base. As a result, this technique is better placed to provide information for all project stakeholders to inform the decision making process throughout the BLC.

The BECs methodology promotes a building stock that is designed, constructed, commissioned and operated to achieve high levels of energy efficiency. Potential benefits include:

- 1) increased energy savings;
- 2) improved building energy-use performance;
- 3) increased thermal comfort leading to increased productivity;
- 4) early detection of potential problems which may be fixed sooner saving on expenses;
- 5) improved documentation of the design philosophy (Section 1.5.8.2).

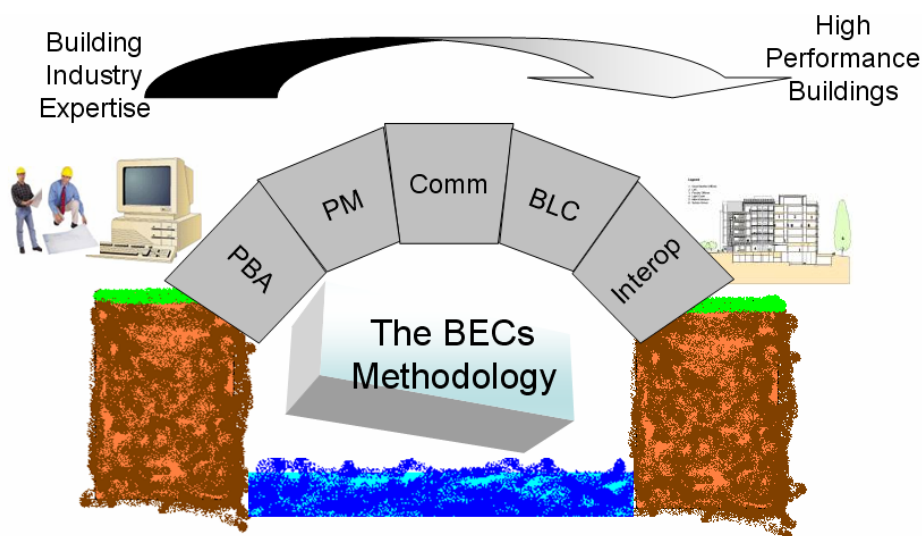


Figure 6-1 – The five key concepts required by the BECs methodology to effectively use existing industry expertise to produce high performance buildings



It is useful at this point to return to Figure 6-1 first presented in Chapter 3 which depicts the concepts required to underpin a successful application of the BECs methodology. It is imperative to draw a set of conclusions pertaining to each one of the key concepts underpinning the BECs methodology (working left to right, over the bridge):

- 1) *Performance-Based Assessment (PBA)*. There is an increasing political will to move the industry towards a more ‘performance-based’ model (for design and assessment) (Section 1.2.2.2). It is widely understood that prescriptive models carry adverse environmental and economic penalties (Section 1.2.2.1). Legislation such as the EPBD (Section 1.4.1) will encourage the industry to take a performance-based approach throughout the BLC. It is envisaged that by employing this holistic assessment of the building’s energy-use, we will see an end to the traditional approach of procuring fashionable products incorporating the latest technology with no understanding relating to the underlying interaction within the building as a whole. The BECs methodology was developed to complement such an outlook by focusing on the ends rather than the means. Armed with these yardsticks for building energy-use performance assessment throughout the BLC, it is envisaged that the technique will support the required behavioural change necessary within the industry.
- 2) *Performance Metrics (PM)*. An increase in high performance buildings is not possible if the practical concerns of operation are not addressed at the outset of the project (Kinney and Soubiran 2004). Just like any other team in the world, a building project team requires quantitative targets to measure its performance. The BECs methodology continually tracks I_r and P_r values throughout the BLC. The platform for monitoring and tracking BECs values builds on the work carried out in the past five years by groups based in Ireland and the US (Hitchcock 2003; O’Sullivan et al. 2004). It is vital that these sets of performance metrics are programmed adequately in order to document the rationale followed during the upstream stages of the BLC in order to facilitate downstream evaluation (Section 3.2.3). This systematic approach for programming would mirror the successful



- ‘programming processes’ carried during the construction phase (project management, etc.). As a result, this is a *bottom-up* approach which looks at the downstream-operation of the building in order to influence what is assessed and predicted during the design periods.
- 3) *Communication (Comm)*. High performance in buildings during the operational phase is only possible through a willingness to communicate by all project stakeholders (Hörschele 1991). However, an enabling language for this communication is required. The BECs methodology provides universally understandable yardsticks of performance measurement. Accordingly, project stakeholders are provided with a language for communication (Section 2.3.4) which is underpinned by a wealth of data and information (Section 2.3.3). Due to the fact that the assessment is universally understandable, all project stakeholders may utilise the results to ‘think’ independently about the footprint left by their design decisions and communicate that evaluation. This is vital in order to ensure that all project stakeholders understand the consequences of the each decision made throughout the BLC.
 - 4) *Building Life Cycle (BLC)*. The old practice of having each building acting as a ‘prototype’ (with no inherent augmentation of knowledge to the broad AEC community) must end (Section 2.2.1). The BECs methodology provides a framework for assessing building energy-use performance at each phase of the BLC. It also provides a repository for capturing the rationale behind decisions at every stage of the BLC in order to evaluate all design decisions (Section 4.5). This is vital in order to build on the lessons and experiences leveraged for successive projects.
 - 5) *Interoperability (Interop)*. The BECs methodology employs the use of a neutral data model (BIM) (Section 2.3.5.3). Currently, the IFC data model has reached a degree of maturity whereby it facilitates the storage of static and dynamic building data. By programming a hierarchy of performance and metrics, the design making process can be captured for future referral (Section 4.5). By enabling access to a variety of tools and technologies, it provides the ideal data warehouse for the BECs methodology.



Knowledge is power; the BECs methodology presents usable information throughout the BLC in order to aid the project stakeholders procure and maintain high levels of performance from a building. Consequently, it offers substantial potential to contribute to the support of economic growth and an energy efficient building stock through improved planning, delivery, operation and maintenance of the built environment.

6.3.1 BECs Values (I_r and P_r)

The mitigation of building energy-use through employment of a set of tools and technologies is facilitated by analysis of predicted or operational performance by comparison with an ideal version of itself (Figure 6-2). This provides a yardstick for measurement of performance which aids cross-discipline communication for all project stakeholders. The universally understandable visualisation aids, offered by the BECs methodology, are sets of ratios which make a facility's energy performance more appreciable. By educating project teams on the heterogeneous agents which affect the energy performance of a building, they gain an insight into the design effects on energy performance *and* occupancy comfort

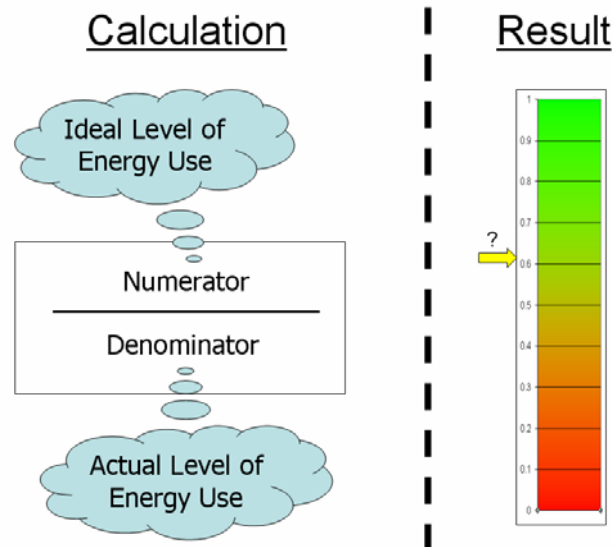


Figure 6-2 – Comparison of predicted/actual operation with ideal operation in order to generate a universally understandable yardstick of performance



The engagement of all project stakeholders utilising their knowledge and experience during any decision making process is vital (especially when assessing elements of that decision that are impossible to quantify on a computer). For example, many HVAC strategies may not be suitable for a particular project (examples include natural ventilation strategies near swamps or rivers where flies become a problem or open source heat pumps located near environmentally sensitive areas). By employing the BECs methodology, disparate systems under evaluation are assigned universally understandable yardsticks of performance underpinned by a wealth of information which account for the interplay of objects within the building that dictate the energy performance of the facility. Depiction of the huge quantities of data is facilitated by *clear* and *concise* graphs that convey the message without ‘muddying’ the message. This facilitates the visualisation of the potential energy performance benefits of HVAC strategies, which are notoriously difficult to imagine (for specialists and non-specialists alike).

BECs values aim to ‘inform’ the decision makers. The system’s potential performance problems become more visible and quantifiable. Additionally, by not accepting any HVAC strategies that do not guarantee adequate levels of thermal comfort, the methodology assures a productive thermal environment for the occupants.

As can be seen in Figure 6-3, the BECs methodology provides two ratios as an enabling language for communication. The first ratio (termed the idealised effectiveness ratio (I_r)) is utilised by the design team (throughout the BLC), while the second ratio (termed the performance effectiveness ratio (P_r)) is employed by the operations teams (post construction).

As mentioned previously, the appraisal of sustainability is carried out by a comparison of building performance with an *ideal* version of itself. This concept is continued during the calculation phases for the two sets of BECs values:

- 1) When generating values of I_r (during the pre-operation phases), the denominator represents how much energy the facility is predicted to require while the numerator represents the lowest possible amount of energy required by the building under ideal conditions (a system-independent configuration of the building model). Post occupancy, the information source for the denominator



becomes the building's BMS. The average of this ratio (over any set time period) presents a final assessment as to the effectiveness of design.

- 2) For P_r , the denominator represents the actual energy-use while the values leveraged from the simulation model are employed as the numerator (acting as the new 'ideal'). As a result, the ratios can be considered as enabling tools for the systematic achievement of the energy saving potential of a facility.

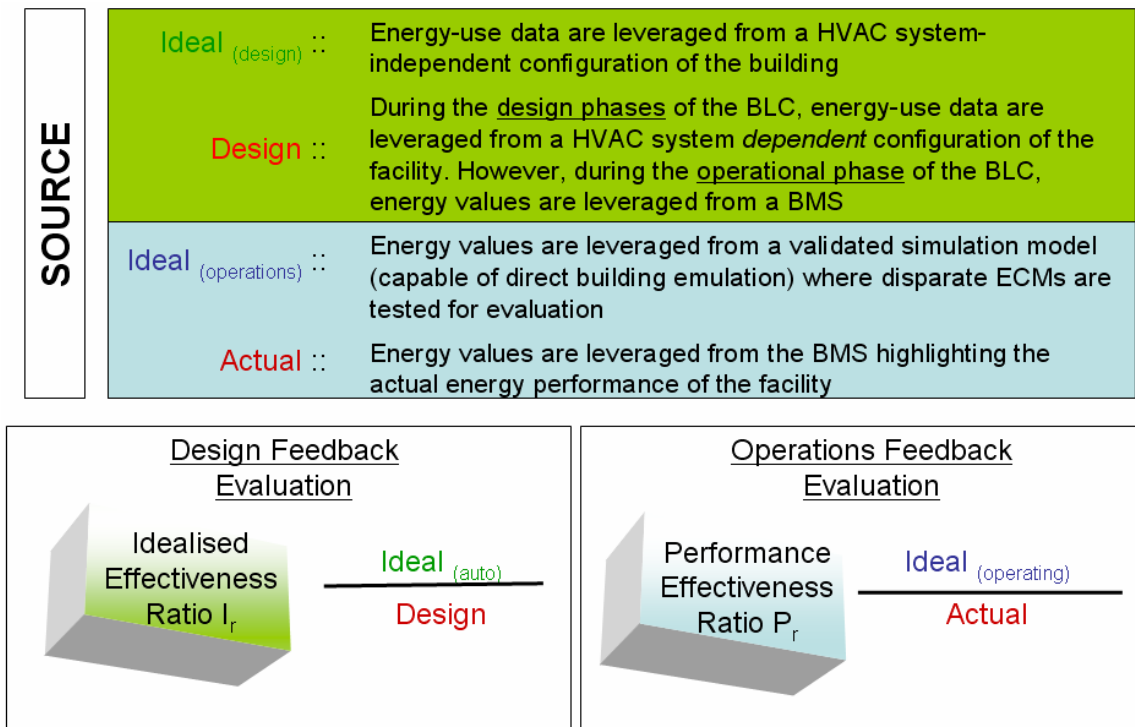


Figure 6-3 – The sources of data for calculation of the two effectiveness ratios employed throughout BLC by the BECs methodology

This research considers BECs values to offer a superior rating system for building performance when compared to many of the popular sustainability assessment frameworks (Section 1.5). Its development was guided by many of the beneficial aspects of these frameworks but the important difference is that generation of ratings does not employ a common model for direct comparison. By employing the 'ideal' version of the building for performance evaluation, adverse handicaps of the rating can be avoided (agents such as disparate space use, building codes and regulations, local climate, surrounding environment are all accounted for in the rating).



Such an assessment framework is noteworthy as project teams are coerced into assessing the holistic consequences of design rather than the optimisation of individual components. By adopting the technique throughout the BLC, project teams begin to foster a more performance-based outlook, always mindful of the end product rather than the ‘project closeout’. Because BECs outputs are easily appreciable (values range from zero to one, with values closer to one highlighting superior performance), the technique becomes universally understandable.

6.3.2 Design Stage Benefits

During the design stages of the BLC, the project shifts through many iterative stages. The BECs methodology offers a means of ‘researching possibilities’ by providing information to guide the selection processes.

At the early stages of design, there are limited pools of information available to aid trustworthy evaluations. However, it is important to provide the design team with an enabling tool for assessment of alternative systems and strategies for incorporation into the building design. By employing early configurations of the building and its systems into two models (the ideal and the design strategy), values of I_r may be communicated to all (facilitating early quantification of the effectiveness). As a result, the design team has a means of qualification and quantification of alternative solutions rather than detailed analysis of a single solution (Section 3.2.1.1.1).

During the detailed design stages, the BECs methodology aids the selection of system components and ensures high values of operational performance through informed design decisions. Disparate environmental design strategies may be assessed which aid the selection processes. Armed with this knowledge, the detailed design processes should give a clearer vision of the end product’s performance (design intent) and what can be achieved (Section 3.2.1.2).

6.3.3 Operational Stage Benefits

Proficient operation of the building is one of the keys to a *sustainable* building stock. High levels of energy performance are not inherited from the design papers or the commissioning tests, a high-performance design must be *operated* effectively. The BECs



methodology provides a language of communication for the building manager and also provides a quantifiable target to achieve the energy saving potential of the facility. By retaining the services of the energy IT consultant (Section 3.2.4), the FM team is educated in the design philosophy and design subtleties which will result in a low energy building. Accordingly, the building manager would be trained to:

- 1) make better decisions;
- 2) spot ineffective equipment which can be replaced with more efficient products;
- 3) recalibrate BMS and components regularly; and
- 4) examine and maintain set-points properly.

When the building is under operation, data from the BMS can be employed to give a quantification of the effectiveness of the final design solution. Values of I_r can be generated to *perceive* exactly who is taking responsibility for the energy performance of the building. However, the BECs methodology also aids the operations team. Values of P_r highlight the operational performance of the facility. Generating higher values of P_r represent a performance target for the building's operations staff.

The BECs methodology does provide an enabling means of improving operational performance beyond design specifications. It is often found that there is significant potential for further optimisation of a building's systems during operation. The fully calibrated whole building simulation model can be employed to provide a platform for improving existing performance; it can be configured with new ECMs and advanced stratagems in order to achieve even greater energy savings (beyond the design plans) (Section 3.2.2.2). Once these new strategies have been agreed upon by all project participants, they are adopted within physical building to improve the energy performance of the facility.

The new simulation model and new sets of BMS data can be utilised by the FM to systematically move towards the new energy saving potential of the building. Armed with BMS data highlighting mitigated energy-use levels, updated values of $I_{r(\text{operation})}$ can be generated in order to improve the overall design ranking providing direct feedback to the design team.



6.3.4 Archiving the BECs methodology

The practice of archiving the design intent has much more value than collecting static piles of as-built documents, drawings and O&Ms which are tedious to read and often found to be outdated or inaccurate (Section 3.2.3.1). In the same way that computer programmers use comments to explain the reasoning behind thousands of lines of code, it is imperative that the building's design and operations team adequately comment on the reasoning behind the myriad of design and operation decisions.

When employing the BECs methodology, a hierarchy of performance objectives and metrics are programmed for referral within the neutral data file (BIM). This serves to provide a repository of information outlining the rationale and intent behind all design philosophies. Through the archiving of these steps in a BIM, a clear picture can be presented for outside scrutiny in order to leverage and augment the hard lessons which though often learned tend to become lost as the next addition to the building stock commences.

6.3.5 Project Stakeholder Benefits

The BECs methodology's yardsticks for performance provide an objective language of communication for building energy-use sustainability which may be understood by the client. As can be seen in Figure 6-1, 'communication' is central within the metaphor of the arch bridge in order to convey this concept's importance.

It is envisaged that through increased communication via the BECs methodology, many beneficial outcomes are possible. The potential benefits are subdivided for each project stakeholder and outlined in the following paragraphs.

Many of the potential benefits from the framework directly affect the occupants that reside in the buildings. For example, the built environment will see an increase in more intelligent buildings catering to the needs of the occupants. A small increase in thermal comfort conditions can drastically improve the output from building occupants and increase satisfaction with the internal environment (Section 2.2.5). The BECs methodology aims to promote facilities with effective management of the internal environment.



The owner/client of the building has much to gain:

- 1) Better buildings mean better business. The methodology systematically attempts to create a platform for reducing the energy bills for the client regardless of the technologies (heat pumps, solar panels, boilers, etc.) employed within the building.
- 2) By employing whole building analysis early on in the BLC, early identification of flaws in design philosophy which are normally impossible to predict until actual operation will lead to fewer mistakes. Late identification of design flaws often leads to *ad hoc* solutions that tend to have limited durability or effectiveness. This reduction in late fixes for design errors will lead to a reduction in capital – and often maintenance and operation – costs for the client.
- 3) By tracking the performance of the building throughout the BLC, the client has an enabling tool to suspend payment in negotiation with the design team if certain project members do not address their sustainability responsibilities (e.g. poor construction leading to inflated levels of infiltration which means increased heating and cooling loads).
- 4) By retaining the services of the energy IT consultant for the management of the BECs methodology, a single point of responsibility is created to manage the dynamic performance of the facility throughout the BLC. This ensures that a building's operation never moves outside its original plans thereby becoming an ineffective facility. This will lead to improved handover, aftercare and feedback for the next addition to the urban development.
- 5) Over time, the bar for attaining a project that is deemed to have high levels of energy performance will be raised due to the proliferation of low energy facilities. This will lead to increased energy savings for the client.

It is imperative to make responsibility for sustainability more transparent as the project proceeds through its iterative stages. The BECs methodology has several aims to address this issue:



- 1) End the practice of project stakeholders paying lip service to a building's sustainable merits without quantitative proof. Those projects that did not 'buy in' to the many heterogeneous facets required to produce an energy efficient facility will be clearly identified.
- 2) Increase the accountability for energy performance sustainability throughout the BLC. Traditionally, it is very difficult to visualise the interplay of a building's elements which dictate downstream performance. However, through early employment of the assessment framework, early identification of the eventual energy saving ability of the facility is a possibility.

There are many inherent benefits for the building stock itself. These include:

- 1) mitigated energy requirements for operation;
- 2) reduced waste and duplication of building information through the open sharing of building data (interoperable environment); and
- 3) increased training for the FM team in the operation of the building:

Finally, there are potentially many inherent benefits within the industry itself:

- 1) Enhanced (and universally understandable) reporting of building energy-use performance throughout the BLC;
- 2) Greater teamwork and communication;
- 3) Increased augmentation of the knowledge through shared learning. This is vital in order to end the practice of each building acting as a prototype or 'black box', with no feed-forward to the next project ;
- 4) A realisation that technology is *not* the answer to the 'sustainability issue'. Armed with this key realisation, a more holistic appraisal of performance will be adopted through all stages of the BLC.

This research appreciates that changing an industry so imbedded in a particular form of operation (Section 2.2.1) is an immense challenge. However BECs was developed to



provide a *platform* for the required changes through increased communication and integration of the industry's communities in order to systematically mitigate the energy requirements. It will take vision on behalf of all project participants to adopt such a framework. However a common thread in the benefits is that, one way or another, society will be the ultimate beneficiary.

6.4 Building Life Cycle Process: Some Considerations

The BECs methodology requires principles of teamwork and increased communication for successful building operation. The client has much to gain from procuring a building that was guided through its iterative life cycle stages by these principles. However, potential facility owners will receive unsatisfactory results if their requirements of sustainability are not clearly specified. As a result, the BECs methodology aims to provide the industry with knowledge of the area in order to make the right decisions from the beginning:

Unfortunately the early design characteristics are often fully developed without the semantics of downstream performance characteristics being fully assessed due to poor communication and enabling media (Section 2.2.3). This problem is exacerbated by the fact that it is often too late to adequately affect the energy saving potential of the building downstream of these fundamental design decisions. *Ad hoc* designs for reduction of building energy-use often lack the reliability or flexibility of early design systems. An increase in integration and communication at the outset of the project is required in order to achieve an efficient building.

As discussed previously, BECs accounts for many of these heterogeneous agents and yet offers a universally understandable yardstick of performance for application throughout the BLC. This research envisages that engaging in round-table discussions would highlight the heterogeneous agents that are not accounted for when employing high resolution system simulation engines. As a result, the beneficial effects seen through successful employment of the BECs methodology will only be enjoyed by projects that adopt integrated design and operations practices founded on a collaborative approach where common goals are set out for everyone to work to. Within the collaborative environment, project teams, as well as project individuals, require:



- 1) good communication skills;
- 2) a willingness to change old processes (with a realisation that the old ways are not necessarily the best);
- 3) an ability to learn new skills;
- 4) a shared holistic vision of sustainability throughout the BLC;
- 5) a respect for the knowledge and experience of other specialist teams;
- 6) imagination and flexibility; and
- 7) an interest in occupants' needs.

In order to move any project through the iterative BLC stages, the problem of responsibility for sustainability must be resolved. This requires the election of a project leader who understands the interplay of design subtleties on energy performance (e.g. structural form, building use, etc.). Traditionally, the leader is the architect; however, their role ends on handover of the project. This research believes that there is scope for an Energy IT Consultant to assume the role. This project participant's understanding of the BLC effects pertaining to design subtleties is unparalleled during the early phases of design. Additionally, they have the experience and domain knowledge of when – and why – specific media should be employed. Finally, they have the ability to creatively solve real world problems while still having a basic and elementary understanding of the underlying principles.

As the project evolves, all design decisions would be related to this project stakeholder who can assess the impacts of the decisions. This person would also manage and keep all information universally accessible in a central location, the BIM, aiding the integrated nature of design.

6.5 BECs Values: Calculation and Application

The mission of the BECs methodology is to systematically mitigate energy consumption in a building while maintaining adequate levels of thermal comfort. It does this by providing a language of communication through furnishing project stakeholders universally understandable yardsticks of building energy-use performance. The



‘language’ takes the form of ratio values which, while prepared by an energy IT consultant, are appreciable by both specialists and non-specialists alike. Armed with these yardsticks of performance, various functions required of project stakeholders may be facilitated with superior information in order to aid the design making process (Figure 6-4).

Building Life Cycle Phase	Function
Early Design Phase	• HVAC System Selection
Design Development	• System's Component Selection
Detailed Design Phase	• Updated Performance Prediction • Insurance of Design • Cost-cutting Impact Evaluation
Construction	
Commissioning Phase	• Updated Performance Prediction • Insurance of Installation
Operational Phase	• Actual Performance Evaluation • Design Feedback • Project Evaluation

Figure 6-4 – Functions which may be enabled by the BECs methodology throughout the BLC

The first of the two forms of BECs values is the Idealised Effectiveness Ratio (I_r). These ratio values were developed as an enabling tool for the environmental design team. Values provide quantitative performance assessment of how well a proposed (or installed) environmental system. It may be calculated at each iterative stage of the BLC by employing enabling sets of data. Once the building’s form has been finalised, values for the ideal do not alter. However, values for the denominator are updated at each stage of the BLC as more accurate data becomes available (Figure 6-5). Ultimately, the design team is provided with a final assessment of design which may be compared with a database of buildings in order to rank the energy-use performance of the project.

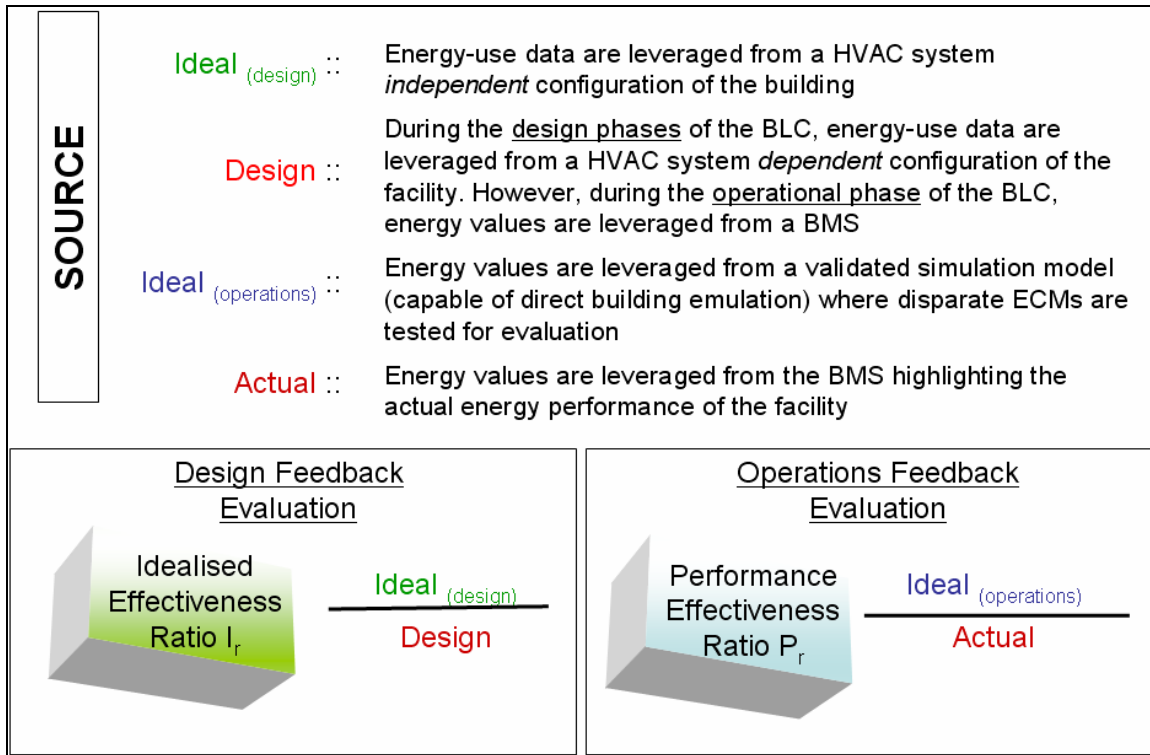


Figure 6-5 – The sources and uses of the two effectiveness ratios employed throughout BLC by the BECs methodology

The second BECs yardstick of performance is the Performance Effectiveness Ratio (P_r). These ratio values were developed to establish an enabling medium for continually tracking *operational* energy performance. These values provide a quantitative vehicle for driving operation towards its intrinsic energy saving potential through a direct comparison of actual performance with ideal performance. These ratio values are calculated through comparison of the building's actual building performance with the performance leveraged from a whole building *system-dependant* configuration of the facility in an energy simulation model (including its geometric form, HVAC, location, etc.).

Despite the simplicity of output, BECs ratio values are underpinned by a wealth of data. As a result, it is vital to consider the underlying data environment. For the BECs methodology, all building data are collected and integrated into a central data product model (termed the BIM). This BIM houses all details of the building in order to facilitate information access for all project stakeholders.



An additional point of significance relating to the BIM is its interoperable nature. This facilitates access to building data by a suite of tools as long they are compliant with the underlying data model's schema. This aids the transfer of information and bridges the information gap between the teams engaged throughout disparate phases of the BLC.

Achieving high levels of energy efficiency requires a *pragmatic plan of action* due to the many disparate and iterative phases inherent in a BLC. It also requires more informed decision making. Accordingly, the BECs methodology addresses these requirements by providing a systematic plan for achieving a facility's energy saving potential by employing the ratio values – underpinned by vast quantities of data – at various stages of the BLC:

- 1) *Early Design*. During this phase of the BLC, the goals and objectives for the facility are standardised. Once the building's form has been finalised, a benchmark of performance can be set by employing a whole building simulation model (Section 2.3.3.2.1.1). Despite the limited information available at this early phase, alternative HVAC strategies can be evaluated using values of I_r . These values give the energy performance of disparate strategies a more tangible and quantifiable appraisal (Section 3.2.1.1.1). As a result, round-table discussions – drawing on the experience of all project stakeholders – can be engaged in to discuss various issues (i.e. economic and environmental impact, comfort, etc.). Accordingly, the 'right' system which best suits the facility and the interests of the project holders will be selected.
- 2) *Detailed Design*. BECs values aid component selection and performance prediction for the facility. However, consideration by all project stakeholders is vital. A budget is synonymous with every project. It is not unusual for the design team to be unable to proceed with every vision they have considered for the facility due to budgetary constraints. Several cost-cutting exercises often need to be carried out during the detailed design and construction phases. Unfortunately, these sessions are often engaged in with absolutely no consideration for the holistic energy performance impacts. This is due to the abstract nature of the effects and the difficulty in visualisation. However, the BECs methodology is



capable of speedy assessments and communication of the results in a universally appreciable manner. Updated values of I_r can be calculated so that only fully informed decisions are made. Any adverse downstream operational efficiency and performance defects become more stark and omnipresent. Additionally, as information pertaining to the system's components becomes more available, the simulation models employed become more trustworthy. This implies that, as the design phase matures, the ratios will give a greater assurance of predicted performance.

- 3) *Commissioning*. Once the building has been built and commissioned, numerous sets of data can be fed directly into the simulation models. New values of I_r can be calculated. As a result, a more accurate portrayal of the envisaged performance can be leveraged from the technique. If large disparities exist between $I_{r(\text{design})}$ and $I_{r(\text{commissioning})}$, all payments can be suspended by the client until the exact cause is located. If any design or construction decisions were made without assessment of the heterogenous effects a settlement may be solicited by the client.
- 4) *Operation (Design Team)*. Once the building has been operation under normal conditions for over a year, values of $I_{r(\text{operation})}$ can be calculated. These values provide direct feedback to the design team highlighting the actual effectiveness of design. However, it is important that the wider context of operation is considered. This can only be achieved through regular communication with the FM team.
- 5) *Operation (Facility Management Team)*. It is vital to continually track energy performance throughout the BLC. This must become a habit. Although equipment improvement promises a better overall system than ever before, that promise is only obtained through regular assessment and monitoring. The FM team and the HVAC design team must meet on an annual or bi-annual basis. This is important, as it lays a platform for:
 - I. evaluating the operational performance of the facility (utilising values of P_r);
 - II. brainstorming alternative operations strategies to increase the performance of the building beyond the original design plans (using the simulation models for the test-bed centre); and



III. discarding ineffective operations leading to sub-optimal performance.

If performance is increased significantly, new values of I_r can be calculated providing direct feedback to the design team. This closes the feedback loop and ends the practice of each addition to the building stock acting as a solitary prototype.

6.6 Future Work

It will be vital to consider the storage of data. Adequate storage for the large volumes of data to be collected over the course of the BLC must be considered. Significant evolution in data storage can be assumed, however it is vital that an adequate environment is employed. Trial implementations of the BECs methodology were inconclusive in highlighting the effectiveness of the IFC data model's capabilities.

Once the industry's ICT tools and technologies have attained a degree of maturity, making them ready for adoption by the industry, future 'real' projects may employ the BECs methodology. This research has developed a set of requirements needed by the industry in order to coerce the development of a suite of integrated design and assessment tools. These tools would all be facilitated with internet capabilities and provide all project stakeholders with easily-accessible objective *yardsticks of performance* underpinned by a wealth of quantitative and *trustworthy* data. The toolkit would be based on the EEMS system as described by Dirk E. Mahling et al. (Mahling and Lehman 2005) and would provide a centralised point of reference for all project stakeholders (with special emphasis on an effective tool for the FM team). It would provide several key functions:

- 1) Create a new internet-based tool that will allow building stakeholders to assess the quality of their projects and see the value of good design. With its multi-media capabilities, it would offer the launch-pad for the methodology to improve the worldwide performance of society's building stock. This tool would provide a qualitative assessment for building energy-use underpinned by a quantitative framework. A graphical user interface capable of seamlessly gathering the input



- from the many disparate tools and technologies, and preparing BECs' value output would greatly aid the development of a more sustainable building stock;
- 2) During any stage of the BLC, it would be possible to assess the quality of design, construction or operation. Effective interaction with the building industry is vital in order for the methodology to be integrated into the *modus operandi*. This would support the refinement of the concepts, the advancement of the techniques and would showcase the added benefits of incorporating BECs into the lifecycle management of a project.
 - 3) The tool itself would facilitate automatic trending and comparison of energy consumption. It would aid the FM team by updating these individuals on the operational performance of the facility. Such quantitative targets would drive the building's operational performance towards its intrinsic energy saving potential. By integrating this functionality to fault diagnosis and detection software, early detection of issues would be possible (which would reduce costs for the facility);
 - 4) Additionally, it would help evolve the IFC data model and existing business models which would encourage industry adoption of integrated software environments;
 - 5) As it is located on the web, instant archiving of climatic conditions, BMS data and occupancy within the building (if adequate sensoring has been installed) would be possible;
 - 6) Certain privileges would be granted to project stakeholders (e.g. the FM would gain the ability to control set points, monitor and control the lighting or HVAC, etc.). This would increase the effectiveness of the role taken by each stakeholder throughout the project.

Such a centralised tool provides a location to assess *and* control a facility. This reduces the time required to identify faults or increase performance. These advantages offer the client higher levels of thermal comfort within the buildings, happier occupants with inherently higher levels of productivity, mitigated energy requirements and lower operational costs. Clients with larger building portfolios would have even more to gain.



Ultimately, the building stock would see a wholesale mitigation in energy-use paralleled by a decrease in CO₂ emissions.

Finally, this research considers that there is significant research value to be gained in the proposed centralised repository of building information. Future research projects could be launched to examine the linkage between design intent and actual performance utilising the BECs methodology using data mining techniques in order to increase the capabilities of the underlying framework.







Appendix A

Glucksman Art Gallery

This appendix introduces the building that was chosen to pilot an implementation of the BECs methodology and presents a brief overview of the example building's environmental design parameters that are deemed pertinent to undertaking the BECs assessment of building energy-use performance.



A.1 Geometry and Layout

The building is a twisting, turning, cantilevered structure anchored into the ground and has a gross area of 2,350 m². The plant rooms have an area of 300 m², the kitchens incorporate 105 m², the toilets occupy 65m² and the dining area encapsulates 150 m². This leaves just over 1700m² for the gallery spaces and circulation routes open to the public.

Since opening, the building has received numerous architectural and HVAC services awards including: RIBA Stirling Architectural 2005 Final 6; CIBSE Best Project Under £20m 2004; and winner of the Thermal Energy Category at the Irish Energy Awards.

Table A-1 displays the specific functions of each floor which must be considered during the zoning process in a whole building simulation model.

Table A-1 – Table outlining the functions of each floor in the Glucksman Art Gallery

Floor	Function(s)
Basement	Kitchen, Consumable Stores, Gallery Store, Toilets, Office, Plantroom
Ground	Dining Areas, Office, Finishing Kitchen
First	Lobby, Security Office
Second	Gallery Area, Toilets, Sales Area
Third	Close Control Galleries, Plantroom
Fourth	Storage Areas, Gallery Spaces
Fifth	Plantroom

A.2 Construction

The building uses cast *in situ* concrete for the basement floors right up to second floor. Above this floor, it reverts to a steel frame with composite walls. The building's exterior is clad in limestone and hardwood. The floors are cast concrete that varies in depth. Only the café has a significant area of glazing.

A.3 HVAC Design

The building is mechanically heated, cooled, humidity-controlled and ventilated. The following subsections outline details of the mechanical plants.

A.3.1 Exhibition Spaces Ventilation



The exhibition spaces are ventilated by a displacement ventilation strategy. Air is supplied at low levels through window floor boxes and other discrete inlets. Return air is taken out of the rooms through the shadow spaces at the gaps between the ceiling and walls. Supply air temperatures range from 19°C in cooling mode to 29°C in heating mode.

Typically within exhibition spaces, tight control of temperature and relative humidity (RH) is required. The air is provided by dedicated AHUs which provide 6 air changes per hour.

One of the important modes of operation frequently engaged during the summer months is dehumidification. The space setpoints are 50% RH and 21°C. As a result, the AHUs must operate by employing the cooling coils (to strip out the moisture and reduce temperature) and the heating coils (to increase the supply temperature to the required level). The two dedicated AHUs are described below.

A.3.2 Wrap-Around Galleries (AHU2)

The spaces being supplied by this AHU are a mixture of double and single height spaces located on the 2nd and 4th floors. The AHU itself is the largest in the building and is composed of a mixing box, cooling coil, heating coil and supply fan. Several terminal reheat coils supplement the supply temperature. Temperatures are maintained at 21°C year-round while the RH is maintained at 50% +/- 20%.

The unit itself was designed to accommodate design day climatic conditions but also a design load of 126 persons. However, despite the regular frequency of visitations by the public, the occupancy of these areas is rarely (if ever) at design conditions. Accordingly, part load performance of this AHU is extremely important given its large capacity.

A.3.3 Close Control Gallery (AHU3)

This AHU (termed AHU3) is composed of a mixing box, cooling coil, humidifier and supply fan. Two terminal reheat boxes are located before the supply inlets to the space. There is also an extract fan for drawing out return air. This AHU manages strict temperature (21°C +/- 1°C). This is the single most important AHU as the space houses the most prized exhibits. However, spaces-use varies with each exhibit. Alternate uses include:



- 1) Small cinematic presentations. Short films are projected onto one wall and all the lighting is turned off;
- 2) Closed off displays behind full height glazing. Priceless exhibits are displayed behind glass at the entry to the space and as a result, no persons may gain entry;
- 3) Some exhibits require intensive lighting which adds to the internal cooling load and visitors are allowed to walk freely around the space.

A.3.4 Basement Ventilation

The lower levels of the Art Gallery contain numerous supply and extract fans. Three of the more significant fan/coil arrangements are discussed below. These zones may be considered as ‘fully mixed’ zones.

A.3.5 Kitchen

The kitchen area contains many units, including large industry refrigerators, cooking hobs, deep fat fryers, etc, which transfer a large amount of heat to the space. The area itself is ventilated by a supply fan and a heating coil. Air is exhausted from the space via extract fan. There is a large flow rate through this unit in order to adequately ventilate the space.

A.3.6 Security Room

This room contains several computers and also the comms server for the building. As a result, there is a large variance in the heating and cooling loads (depending on the external climatic conditions). Due to the fact that this room may be occupied on a 24 hour basis, it contains its own dedicated AHU which is composed of a mixing box, cooling coil, heating coil and supply fan. Air is exhausted by a dedicated extract fan.

A.3.7 Gallery Store

This area has a dedicated AHU for maintaining *strict* temperature and RH control. This is vital in order to secure a safe internal environment for the art works contained within. The AHU is comprised of a mixing box, cooling coil, heating coil and supply fan which provides 100 litres/s. Air is exhausted from the space through a separate extract fan.



A.4 Water Services

In order to provide the ventilation units with sustainable sources of hot and chilled water, an innovative chiller unit and design was employed. Well tests confirmed the availability of a clean, thermally stable water source (with a steady temperature of 11°C) located in the alluvial gravel deposits to be found deep down in the River Lee's basin. The chiller unit, termed a Ground Energy Thermal Transfer System (GETTS), minimises energy consumption for the building by providing both heating and cooling water simultaneously. The plant minimises the reliance on non-renewable sources of energy by exploiting the water in alluvial gravel deposits beneath the site. In doing so, energy consumption has been reduced to 25% of the levels expected from conventional chiller and boiler heating systems.

The building operates through two water cooled chillers. They simultaneously generate chilled water at 6°C and heating water (referred to as low grade hot water (LGHW)) at 45°C (30°C when providing cooling only). Any excess heat or coolth is transferred to ground water through plate heat exchangers. The ground water itself is sourced from two 12 metre deep wells. Excess water is discharged directly to the river. When the groundwater is cooled, it is acting as a heat source in the winter months and the rejected water temperature would be approximately 6-7°C. When the groundwater is heated, it is acting as a heat dump in the summer months and the rejected water temperature would be approximately 19-20°C.

At capacity, the GETTS has a capacity of 170kW cooling and 200 kW heating. This system can provide of CoP of 8 (1 kW of electrical power in the chillers can provide 8 kW of heating and cooling energy).

Two gas-fired boilers provide back-up to the GETTS and also provide high temperature water for the building (referred to as low temperature hot water (LTHW)). This high temperature water is utilised by the trench heating, radiant panels and radiators.



A.5 Internal Environment

The Glucksman Art Gallery houses many areas with disparate functions. As a result, the internal conditions that must be controlled differ somewhat. A generic overview of the internal conditions can be seen in Table A-2.

Table A-2 – The environmental conditions in the Glucksman Art Gallery

Area	Max Ventilation (m ³ /s)	Summer Temp (°C)	Winter Temp (°C)	Relative Humidity (%)	Outside Air (l/s/person)
Foyer, Second & Fourth Floor Galleries	4.0	19	24	50 +/- 30	12
Close Control & Multi-Media Rooms	0.86	19	22	50 +/- 5	12
Café	2.0	25	20	50	15
Private Dining	1.0	25	20	50	15
Gallery Store	0.1	19	19	50 +/- 5	10

The numbers of persons used as input for design parameters (during the detailed design stages) are absolute maximum figures. These figures drive the design conditions used to find the maximum loads on the HVAC system. However, they do not reflect the frequency or distribution of people visiting the public building in a real life scenario. As a result, when attempting to undertake an assessment of part-load operation, it is vital to determine a more accurate assessment of visitors to the gallery. This is carried out to reflect occupancy in the café (maximum occupancy occurring during mid-day lunch) and in the gallery as a whole which are subject to random events such as school tours (during the mid-afternoon) and a higher density of visitors during the weekends.

The building is considered to be a closed envelope (it is not designed to allow natural ventilation flow through the building; all rates of ventilation air are assumed to be mechanically moderated). However the private dining and the café *may* be naturally ventilated (by opening large glazed full height window areas) during the summer months to avoid over-heating. This is at the building manager's discretion.

The building envelope is considered to have been design and constructed to best practice. As a result, the design team consider that all infiltration rates (the unsolicited flow of outside air through the building) can be taken at 66% of suggested values found in



building guidelines such as the CIBSE Environmental Design Guidelines ((CIBSE 1999)).

The density of electrical equipment is extremely low. Only the security room and a small office on the second floor contain computer terminals and other small electrical equipment. Beyond this, there is a very low distribution of electrical devices within the building.

A.6 Design Expectations

The design team expect energy consumption to be 400,000 kWhr, or 175 kWhr/m²/annum (Kennett 2005) for the assumed hours of occupation.





Appendix B

The tool's and technology's issues during the Glucksman Art Gallery Assessment

Appendix B discusses the details of undertaking the BECs assessment for the Glucksman Art Gallery. The systematic approach required for employing a whole building energy simulation model and utilising BMS data is outlined along with any barriers that were encountered (such as inadequate capabilities in the tools, technologies or environment).



B.1 Geometric Building Description

The building's architect required a dramatic effect to be created for the onlooker from the exterior, as well as the interior, of the facility. As a result, the structure of the building incorporates several split-level floors, curved walls, extruding windows and a cantilevered floor structure. These geometric and spatial elements truly test the data translation capabilities of the tools, technologies and environments employed by the BECs methodology during its early phases.

As discussed in section 4.2, ArchiCAD™ (an IFC-compliant 'industry-standard' CAD software package) was employed to describe the first instantiation of information in the BIM. However, a certain amount of foresight is required by the user at this early stage. In order to generate a view of the building that can be specifically translated for use in a whole building energy simulation model, certain model generation techniques must be employed. These techniques include effective zoning of the building and exclusion of entities not deemed pertinent to the assessment to the simulation. There is a lot of information freely available on the web describing effective zoning for downstream input to simulation packages (for instance, several pages that discuss this subject come bundled with EnergyPlus itself).

The building's disparate areas were zoned separately according to activity, room control and mechanical delivery of the environmental conditions. These zones were then configured in the software and assigned descriptive names. No difficulties were encountered when describing the building's walls, windows, slabs, roofs, zones, etc, in its own proprietary environment. The description was then mapped onto the IFC schema in order to facilitate transfer to a variety of media that may be employed throughout the BLC. The next step was to import the current instantiation of the BIM into Solibri Model Checker; in order to validate the geometry (see section 4.3).

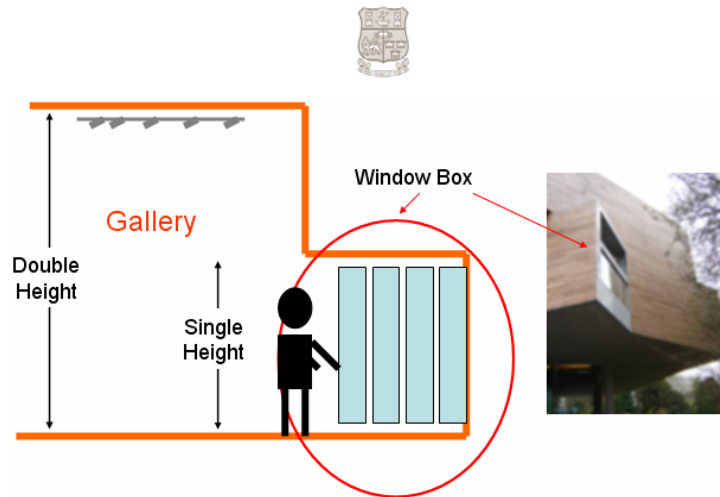


Figure B-1 – Picture and section through one of the gallery spaces highlighting the single height window box which protrudes out from the building

Unfortunately, this step was not seamless and one critical issue did arise. The building's structure incorporates several pop out gallery window boxes. These boxes tend to rise up from the gallery floor to several feet above head height. However, the rest of the space is a double height space (as seen in Figure B-1 which takes a section through part of the gallery space). Early translation tests (for these spaces) highlighted an inability by ArchiCAD to describe this geometric aspect of the building in the IFC schema (walls were truncated and a roof section was missing when viewed in Solibri). As a result, the pop out box spaces were zoned separately with a view to manually configuring them back together downstream in EnergyPlus.

Once the alteration to building's description was completed and the full geometric and spatial instantiation was validated in Solibri Model Checker, it was possible to move onto the next step in the chain: configuration of the building in the whole building simulation model.

The IFCtoIDF utility is employed to translate the geometric description (from the neutral data file (IFC)) into EnergyPlus' proprietary input file (termed IDF for EnergyPlus). Unfortunately, several issues arose during the translation. This middleware software utility was unable to deal with (1) the curved walls; (2) split level zones; and (3) several walls, roofs and slabs. As a result, the original description in ArchiCAD had to be simplified to ease the translation process for two of these three issues:



- 1) The curved walls were broken up into a series of straight walls at discrete angles to each other. It was necessary to employ the use of calculation methods in order to emulate the original structure and maintain the internal volumetric space;
- 2) The double height spaces had to be split completely into single height spaces with a dummy slab separating them at mid-height. This was carried out in the understanding that downstream manual configuration would have to be carried out in order to emulate the actual zones (i.e. remove the dummy slab and reassign the two zones into a single ‘double-height’ space).

Unfortunately, no amount of model simplification would aid the translation of several slabs, roofs and walls. At this stage in the methodology, it became obvious that these entities would require manual configuration of EnergyPlus’ input file post translation.

The manual configuration phase - required to describe the Glucksman Art Gallery’s spatial layout - was extremely tedious, time consuming and error prone. It required significant expertise from the user and the use of a text editor (to manually configure the file) and a DWG viewer (to validate the configuration). Many man-hours were spent setting up the building in this way. Any amendments or new entities had to be: given 3-D co-ordinates; interfaced with the correct zones; and finally manually validated in the CAD software tool. Unsurprisingly this phase of the assessment was one of the most tedious periods. The user had to upload the resultant DWG file in order to tease through the 3-D maze of lines and carefully locate the positions of the walls, slabs, roofs and windows. The phase itself - which *was* envisaged to be ‘automated’ - was found to be extremely labour intensive and highlighted clear deficiencies in the capabilities of the translation software.

Finally, all walls, slabs, windows and roofs had to be assigned with properties (composition and thermal characteristics). Once again, this required manual configuration and in the absence of a database describing the properties of these entities, it was necessary to research these data. This process inflated - the already significant - amount of time required to prepare the geometric model. The final conclusion drawn during this phase of testing is that the tools and environments are not sufficiently mature and are not ready to be employed within the industry.



B.2 Whole Building Energy Performance Simulation: Boundary Conditions

The internal heat gain for the building can be accounted for in the simulation model by the configuration of assumptions pertaining to human bodies, lighting, computers, office equipment and other agents. It is vital that these assumptions are adequately configured. Under-estimating their effects may result in an unfair evaluation of the environmental design by implying poor part-load performance (and the reverse can be assumed for over-estimation of their effects). The values used in the Glucksman simulation models are referenced from estimations in the CIBSE environmental design guidelines (CIBSE 1999). The following paragraphs in this section briefly outline the boundary conditions which were manually configured in the system simulation models.

The maximum numbers of persons within the zones were taken from the design conditions which were outlined in the building's O&Ms. However their distributions (and maximum occupancy time schedules) within the disparate zones were generated from site visits (and staff interviews) in order to give a fairer reflection of the associated sensible and latent gains. This is imperative in an exhibition space that requires an extremely tight maintenance of internal environmental conditions but still cater towards many disparate occupancy levels (as visitors come and go).

It is vital to account for the lighting loads in a space. A significant portion of the electrical energy used by a light fixture is ultimately released as heat (through conduction, convection or radiation). The proportion of heat entering the space depends upon the type and location of the light fittings. As a result, some of this heat may be transmitted to the building structure, depending on the manner in which the luminaire is mounted. It was vital to note which lighting fixtures were suspended/wall mounted/ up-light etc so that they could be correctly configured in the model.

The 'Environmental Design' reference guide published by CIBSE defines air infiltration as "the unintentional leakage of air through a building" (CIBSE 1999). Therefore, it is of paramount importance to adequately describe the infiltration for a building (as it can represent a significant alteration in the heating or cooling load). Additionally, it is important to note that the building is situated on a sheltered site (especially from the prevailing SW winds). As a result, all suggested infiltration factors taken from building codes are reduced by a factor of 33% as suggested in the reference material.



B.3 *HVAC System Simulation Models*

As outlined in section A.3, the HVAC system consists of: three main AHUs; several fan coil units and extract fans; several space heaters; and some natural ventilation strategies. The hot water is provided by two separate hot water loops (at temperatures of 80°C and 50°C respectively). The chilled water is maintained at 6°C. Several spaces within the building are heated via one - or through a combination of – underfloor heating, radiator, radiant panel and trench heating. As the radiant panels, radiators and trench heating systems are all supplied with hot water from the same boiler circuit, they may be conglomerated into one object on a ‘zonal’ basis (within the simulation model). This minimises computer resources and avoids unnecessary resolution. The air circuits were individually configured along with the components on the plant loops.

It was envisaged from an early stage that the configuration of these systems would be a time consuming process. Manual configuration of the input file for an EnergyPlus definition of a HVAC system is an iterative process which is extremely non-user-friendly and extremely error prone. Trial system simulations begin with a run period over a small set of days (usually a summer and winter design day in order to test the heating and cooling plants within the building). Next, the user must begin to move through the iterative steps as seen in Figure B-2:

1. The first step is to prepare the input (this consists of loops which contain the wet and the dry sides of the HVAC plant). Care is taken to: ensure all node names are matched together; system controllers are correctly configured; and the systems are laid out to emulate the real facility’s design. Manual configuration of larger systems may take several days;
2. The second step is to run the input file through the EnergyPlus engine. Upon completion of this step, EnergyPlus’ compiler will display the success/failure of the run and any additional errors that may have been encountered;
 - a. If errors were encountered, they are noted and the input file is checked before returning to step 1;
 - b. If no errors were encountered, one proceeds to step 3. Once again, it may take several man-hours before the user arrives at this step;



3. The third step entails a manual ‘eyeball’ check of all system process conditions that are experienced within the simulation environment. These process variable conditions may include: plant outlet temperatures; flow rates; on/off time schedules; set points; etc. Additionally, internal environmental conditions are checked (e.g. adequate internal temperatures, relative humidity, etc).
 - a. If exceptions to process conditions are found (e.g. zero flow through the heating coil during the winter design day), it will be necessary to re-address the input file so that it can be ‘tweaked’ accordingly before returning to step 1. This is one of the most time-consuming processes encountered during the manual configuration. Due to the error prone nature of manual configuration, it generally must be repeated several times and can take several working days;
 - b. If no errors were encountered, one proceeds to step 4;
4. The simulation model is ready. The dates to ‘start’ and ‘finish’ the simulation are prepared so that a full simulation of the building can be carried out.

This systematic approach for manually configuring a model works for small systems as simulation runs take under a minute. Additionally, the time required to manually configure the models does decrease as the user’s experience increases. However, as the magnitude and complexity of the systems increase, the time required by the simulation engine increases exponentially (Figure B-3). An example of the iterative processes involved in testing and tweaking the input file is described in the report (described in the following pages). These pages highlight the difficulties with model configuration and the time-consuming nature of the practice.

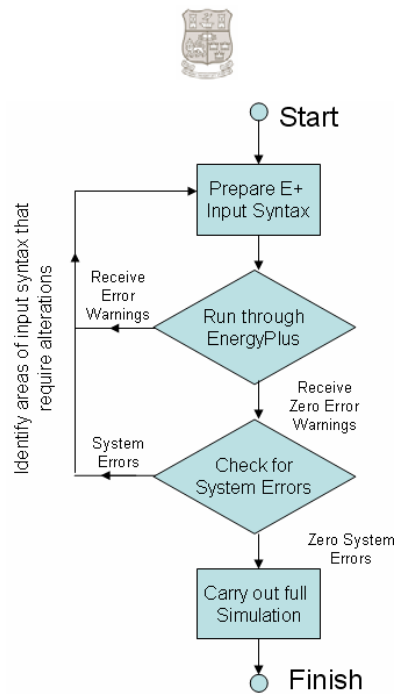


Figure B-2 – Flowchart highlight the systematic approach employed for configuring a system simulation model in EnergyPlus

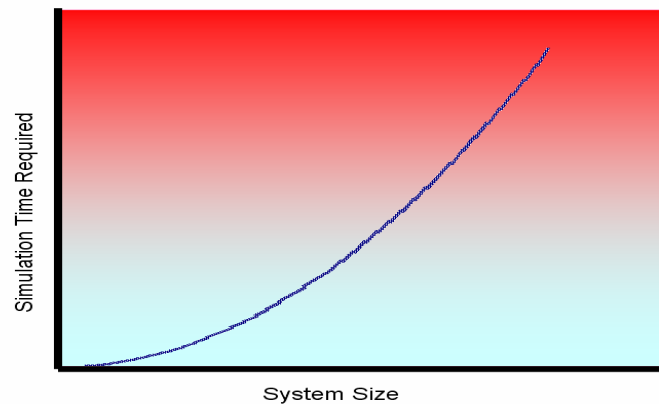


Figure B-3 – The large increase in time required by the simulation engine as the magnitude of the system increases



Report: Brainstorm session to overcome thermodynamic simulation problems in an EnergyPlus simulation.

Attendance: Dr. Marcus Keane, Elmer Morrissey and John McCarthy

Problem: Inability to control relative humidity conditions in controlled zones

Date: February 2nd, 2005

Description of problem:

Air Handling Unit #3 (AHU3) in the Glucksman Art Gallery mechanically services two controlled zones. Both zones require extremely tight control over temperature and relative humidity due to the delicate nature of the artefacts that will be periodically housed within. During the summer and winter months, conditions of 21°C and 20°C (respectively) and 50% Relative Humidity (rh) must be maintained.

Currently, we have operating system simulation of AHU3 which is providing adequate winter conditions of 20°C and 50% rh. This means that the humidifier and reheat coils are responding to climatic shifts as expected. However, during a typical summer day, several relative humidity ‘spikes’ are experienced around the hours of 11am and again at 7pm. These spikes are occurring randomly with a bandwidth of 55% to 60% rh. This situation is wholly inadequate for the tight control required in the zones. The temperature control is operating adequately which leads us to believe the problem lies with the cooling coil as this component controls the RH for the zones.

Previous attempts undertaken to adequately control RH

Experience has shown that on occasion, systems must be oversized in EnergyPlus in order to illicit realistic component nodal output from the simulation model that mirrors actual performance. Thus, when experiencing conditions of 70-80% within the zones (operating with a cooling coil that is autosized to adequately control a zone), initial ‘flags’ pointed to an undersized cooling coil. The object input into EnergyPlus that controls system sizing for autosizing an AHU is the ‘SYSTEM SIZING’ object described in the idf file (figure 1). The vast majority of generic values for sizing AHU components are input from here. It was here that the problem was first tackled and assessed. Cooling condition temperatures and moisture contents were iteratively reduced in order to ‘drag’ the relative humidity in the spaces from an average of 74% (cooling supply temperature of 18°C and moisture content of 0.007kg/kg) to an average of 53% (cooling supply temperature of 4°C and moisture content of 0.004kg/kg). This left the system simulating under more tight control, however we were now left with an oversized cooling coil and the unfortunate issue of experiencing two successive spikes in RH. The oversized cooling coil is expected and the figures can be examined further downstream of the analysis work on the project. However, the nature of the spikes could not be explained due to the unexplained random nature of their occurrence. All schedules relating to plant and load operation were double checked in order to account for these irregular shifts in zone conditions, but the root of the problem was not highlighted.

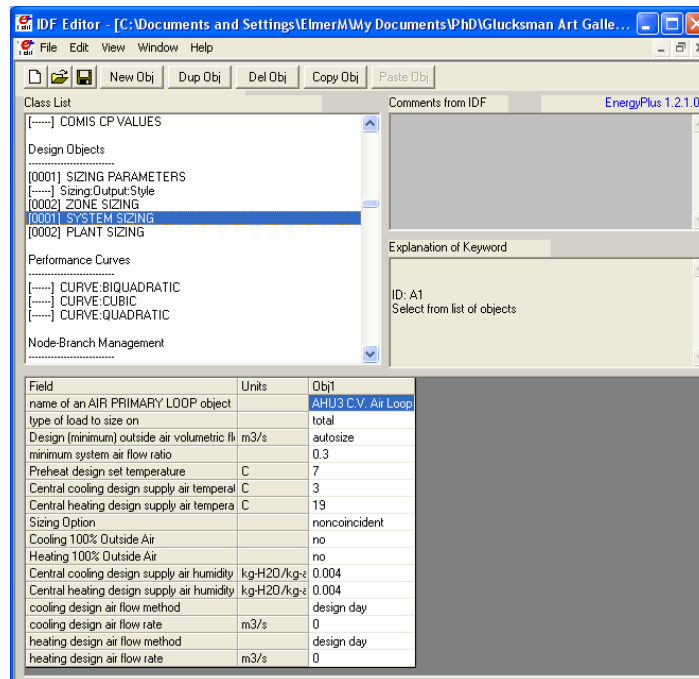


Figure 1 – A snapshot of the System Sizing Object as seen from IDF Editor

Brainstorming problem with Marcus Keane and John McCarthy

The problem being experienced was a latent problem leaving only four possible sources:

- People;
- Infiltration into the space;
- Mixing Box Control (too much outside air);
- EnergyPlus code error.

Initial investigation of the problem commenced with analysis of the ‘people’ load. People add an element of latent load to the system however the schedules of time that people were occupying the zones was outside the two spikes experienced by the AHU. However, as a means of excluding people as a possible factor, schedules were altered. These schedules made no impact on the system (a large spike was still occurring at 11:00). As such, we moved our search onto infiltration. This source was quickly ticked off the list as a minimal value of $\sim 0.75 \text{ AHC}^{-1}$ was set at all hours of the days and therefore this value could not account for either moisture spike.

This moved the search onto ‘C’, Mixing Box Control. The input object controller is termed CONTROLLER:OUTSIDE AIR. As seen in Figure 2, the minimum amount of fresh air can be set to a fixed minimum or a proportional minimum amount of fresh air. Two additional inputs in this field are ‘maximum outside air flow rate’ and ‘minimum outside air flow rate’. It was quickly noted the high values of RH in the outside air may be responsible for the high levels of RH within the spaces. Several graphs were generated in EXCEL to render a high resolution portrayal of the problem.

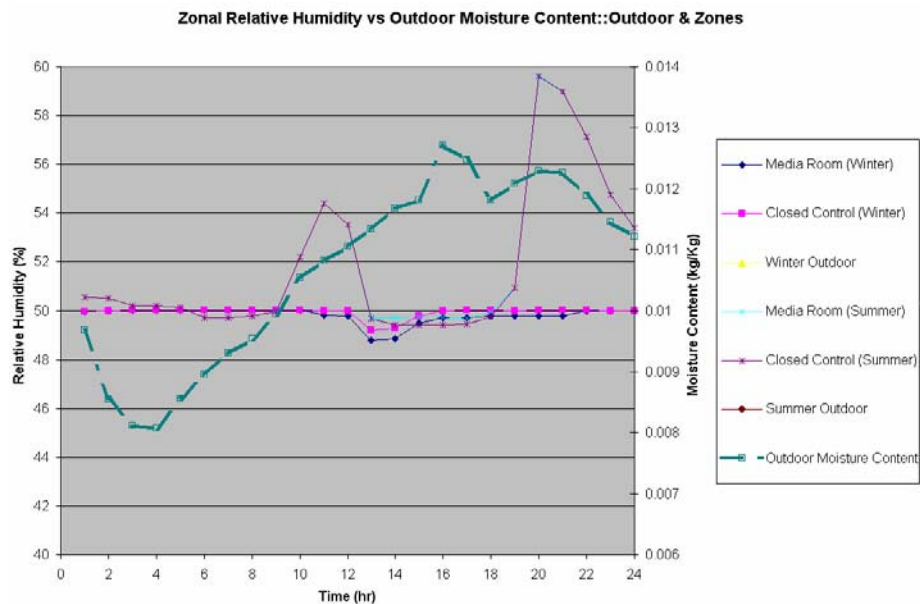


Field	Units	Obj1
Name		AHU3 OA Controller
EconomizerChoice		ECONOMIZER
ReturnAirTempLimit		NO RETURN AIR TEMP LIMIT
ReturnAirEnthalpyLimit		NO RETURN AIR ENTHALPY LIMIT
Lockout		NO LOCKOUT
MinimumLimit		FIXED MINIMUM
Control_Node		
Actuated_Node		PROPORTIONAL MINIMUM current
		PROPORTIONAL MINIMUM default
		FIXED MINIMUM choice
minimum outside air flow rate	m3/s	<BLANK>
maximum outside air flow rate	m3/s	autosize
temperature limit	C	19
temperature lower limit	C	4
enthalpy limit	J/kg	0
Relief_Air_Outlet_Node		AHU3 MB Relief Air Outlet Node
Return_Air_Node		AHU3 Return Fan Outlet Node
Minimum Outside Air Schedule Name		
Name of VENTILATION:MECHANICAL object		

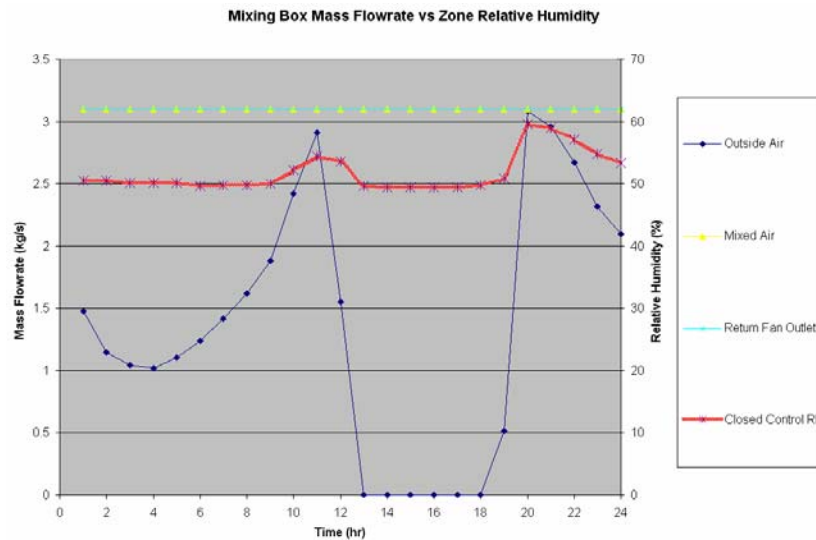
Figure 2 – A snapshot of the CONTROLLER:OUTSIDE AIR from IDF Editor

First Run:: Fixed Minimum @ Autosized max & min Outside Air flow rates

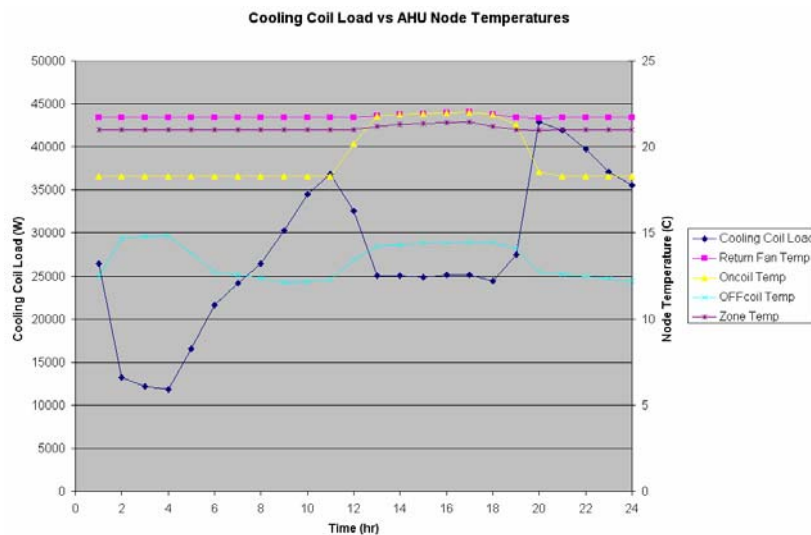
In the first run, we generated a set of graphs associated with a fixed minimum limit of fresh air and autosized maximum and minimum fresh air flow rates. The following graphs were generated (zone temperature control was simulated adequately in winter so these graphs are omitted):



The above graph depicts the spike which is experienced in the summer months from 09:00 to 12:00 and again at 19:00 to 24:00. High moisture content is also depicted on the graph for the outside conditions



This graph depicts a large flow of outside air into the AHU. This intake increases up to a local maximum of 2.9 kg/s at 11:00. The sharp increase in outside air - with its elevated levels of moisture content - into the system leads to an increase in RH. This in turn leads to the cooling coil being unable to achieve its setpoint. The resulting action by the system is to set the outside air intake to zero in order to regain the 50% max humidity. This situation reoccurs again at 7pm with an increased flow of outside air.



This final graph displays the nature of the problem, as the outside air flow rate increases dramatically from the hours of 08:00 to 11:00, the cooling coil load increases, however, once the outside air flow rate is set to zero, the cooling coil load drops dramatically. As can be seen from the graph, (between the hours of 13:00 and 18:00) return fan outlet temperatures and on-coil temperature become one and same. This is due to the absence of any fresh air. Needless to say, zero fresh air during these occupied hours is entirely unacceptable for the system.

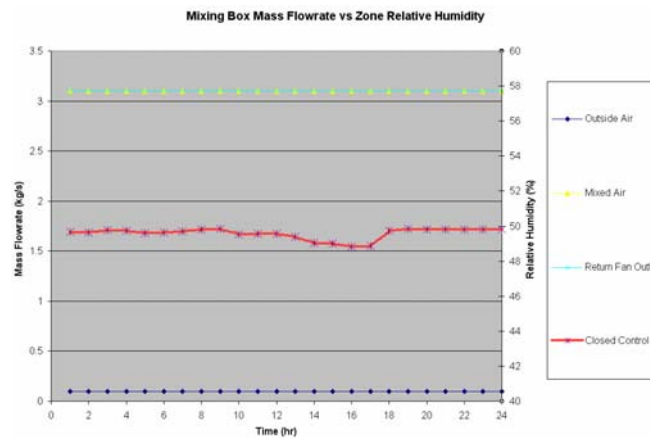


Second Run:: Proportional Minimum @ Autosized max & min Outside Air flow rates

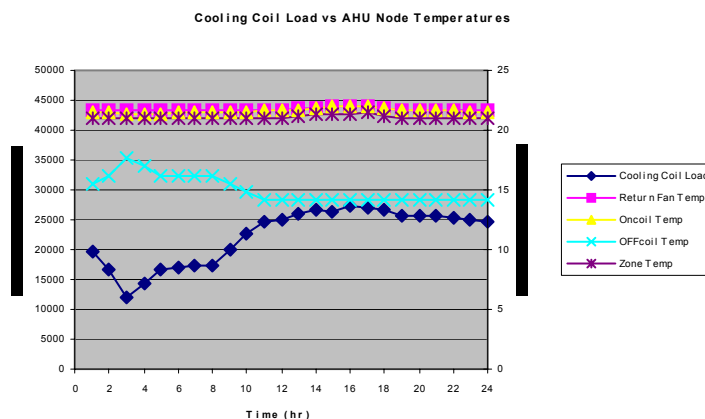
In this run, the graphs displayed similar figures to the first run. The only difference in input into the file was changing 'Fixed Minimum' to 'Proportional Minimum'. It was now evident that autosizing outside flow rates was the root of the problem.

Third Run:: Fixed Minimum @ 0.08 kg/s min & max Outside Air flow rates

In this run, the outside air minimum input was returned to 'Fixed Minimum' however autosizing the minimum and maximum outside air flow rates were altered to values of 0.08 kg/s for both fields. The following graphs were generated:



From this graph, it is immediately evident that with a constant low level outside air-flow into the system, the cooling coil has no difficulty in controlling the system to a constant 50%rh

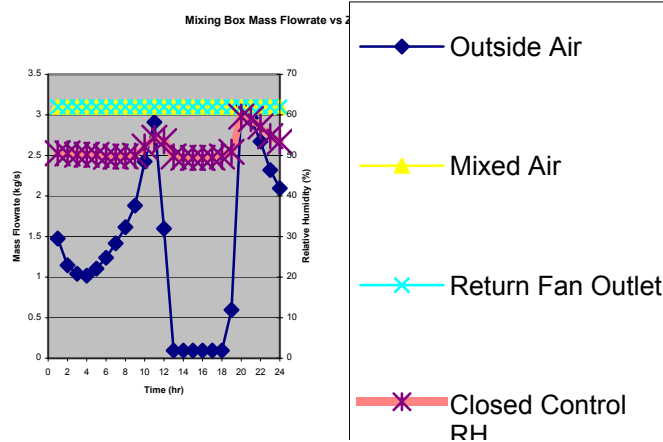


It is clear from this graph that despite with a slightly higher off-coil temperatures over the day, there is a large reduction in cooling coil load despite the tighter control in RH in the space



Fourth Run:: Fixed Minimum @ 0.08 kg/s min & autosize max Outside Air flow rates

The only change to this input is to return the maximum outside air flow rate to 'Autosize'. The following adverse results were elicited from the simulation engine.



Here we can see that we are returning to our situation of a large increase in outside air into the system at similar hours which is displaying similar undesirable spikes once again.

Future examination

The cooling coil was undersized in previous efforts to gain tight control. Now that we have a simulation delivering tight RH control, the AHU sizing can be altered in order to maximise savings for the coil. These tests will be done iteratively so that the cooling coil profile is graphed for a minimum coil load.

As noted in Figure B-3, the time consuming nature of the configuration process for large models does not lend itself towards speedy holistic simulations during testing phases. With this in mind, the building's many disparate systems were broken down into smaller – more manageable – pieces. This eased step #2 in the testing phase (due to speedier identification of errors by EnergyPlus). Once all errors had been ironed out of the individual models, they were conglomerated in order to iron out any errors in a holistic model (step #2 for a holistic model).

B.4 Actual Energy Monitoring: BMS

The BECs methodology requires the archiving of process variables in an open environment. Such a framework would make it possible to assess performance - on a



holistic and component level - by many disparate tools. In order to employ the methodology for the Glucksman Art Gallery, it became necessary to extract data from the vendor's proprietary environment. This would facilitate concurrent access to process variables by any tool. During this research, all BECs ratio values were calculated and displayed in Microsoft Excel.

The BMS in the Glucksman Art Gallery was installed as a *management* software tool only. As such, it facilitates real time assessment of process variables (temperature, relative humidity, on/off operations, set points, etc). Alterations to set points can be facilitated by this tool (if one has the designated security clearance). However, all data are stored in the vendor's proprietary environment. Graphs – describing a process variable's historical profile– are launched on a web browser, however, only one process variable may be selected at any one time. The environment does not facilitate analysis or assessment of the information which would aid holistic appraisal of performance.

Accessing and automating the storage of data from the BMS was not easy. The BMS' vendor had to be contacted in order to procure the IP mapping of the sensor network. Unfortunately, once this had been secured, there were still many issues associated with eliciting performance information from the BMS. For instance, it became obvious that the software itself was not archiving some sets of vital data (e.g. on/off operations, percentage of re-circulated air in the AHUs, etc). This problem was exacerbated by inaccurate sensor readings. The box below highlights a typical example from BMS readings associated with AHU3 (Section A.3.3) on a particular winter day in 2006:



An initial eyeball assessment of the BMS' GUI supposedly informs the user that the system is currently tempering 100% fresh air. However, external sensors recorded ambient air conditions at 5°C. The temperature conditions of the air - as recorded by another sensor – before it enters the cooling coil (the first energy tempering device in the AHU) were recorded at 17°C. Therefore, the system *must* have been re-circulating some exhaust air. This problem is exacerbated by temperature 'drops' in the air stream across supply fans (the final device in the AHU). Needless to say, this is an *impossible* event given the air tight nature of the unit itself.

The text box above - which describes just one single event - highlights two concerns associated with BMS

- 1) Poor maintenance of the BMS system itself;
- 2) The untrustworthy nature of the sensors installed in the building.

It is obvious that regular (and systematic) maintenance of the BMS is required. However, these checks could be aided by a form of 'checking' in the archiving of the process variable. Logical searches for errors could be automated which would furnish the archiving software with a degree of intelligence (throwing error flags if temperatures are decreased across fans, etc). Such intelligence may be updated throughout the BLC in order to augment the knowledge gained from past experiences.

B.5 Data Warehouses

This section discusses the distinct data sources required for BECs value calculations throughout the BLC.

All references to the resulting data warehouse locations are stored in the BIM in order to aid downstream evaluation (Section 4.5). Figure B-4 highlights a sample hierarchy which is programmed in order to capture the various models which are required during the early design stages in order to aid the alternative system selection process (Section 5.3.1.1). Each one of the performance metrics stores a reference to the energy simulation



models and the resulting output. Accordingly, downstream evaluation of the data which influenced the decision making process may be evaluated. Figure B-4 highlights a sample hierarchy where PO denote performance objectives and PM denote performance metrics.

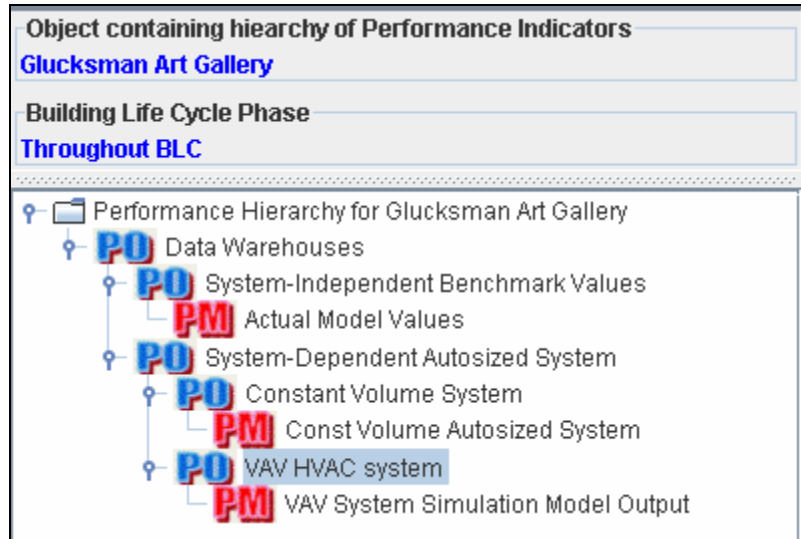


Figure B-4 – Screenshot from EArchive highlighting the referencing of data warehouse locations in the Glucksman Arty Gallery’s BIM

B.5.1 Early Design Phase

During the early design phase various simulation models are required to for alternative system selection using $I_{r(\text{early design})}$ (Section 5.3.1.1). These simulation models are defined by two modes (system-independent or system-dependent):

- 1) The first mode for the simulation models is a *system-independent* prediction of ideal performance (offering the lowest levels of energy required to service individual spaces);
- 2) The second mode of simulation model is a *system-dependent* prediction of ideal performance for alternative HVAC systems which are being proposed as possible HVAC system to service the spaces.



B.5.2 Whole Building Benchmark Model

Data leveraged from this building energy simulation model represents the *minimum* levels of energy-use required to maintain adequate levels of thermal comfort within the building's spaces (Section 2.3.3.2.1.1). It is important to note that this model is a '*system-independent*' energy simulation. The purpose of this simulation model is to offer data which may act as a 'binding target' for qualification of 'actual system performance' during calculation of I_r values throughout the BLC⁸. Accordingly, it is vital to account for both the fresh air requirements and the tempering of conditioned air in order to maintain adequate thermal comfort in the spaces.

In order to account for the minimum levels of fresh air required in the building design regulations (CIBSE 1999), a 'ventilation' object is configured within the model to simulate the required flow of fresh air into the zone. This configuration supports the model's philosophy of representing a system-independent configuration of the building as there is no requirement for the input of components which may lead to energy-tempering inefficiencies (e.g. part-load performance of fans). For this model, fresh air space requirements are coupled with the number of people in the zones. Accordingly, the expected numbers of persons⁹ is multiplied by the minimum fresh-air-per-person requirements (referenced in the local environmental design guidelines (CIBSE 1999)).

The performance of an *ideal* HVAC system may be leveraged from 'Purchased Air' objects (US-DOE 2005). These energy tempering devices may be thought of as 'ideal energy-tempering systems', with 100% efficiency, that produce a supply air stream at the specified zone inlet conditions (i.e. the user specifies the zone inlet *temperature* and *moisture ratio*). Within this model, this energy tempering device is the sole conditioning component configured for each space in the model (one 'purchased air' object per zone). For the BECs methodology's benchmark model, the purchased air component is operated as a component with:

⁸ It is not envisaged that these target levels of building energy-use will ever be achieved by an actual HVAC system due to inefficiencies in actual physical components

⁹ This distribution may be gathered in a number of ways: surveys and visitations from similar buildings; client expectations; etc. For the Glucksman Art Gallery, it was gathered by several interviews with staff.



- 1) an infinite heating and cooling capacity;
- 2) fully re-circulated air (no inlet for outdoor air is required as it has already been accounted for in the ‘ventilation’ object);
- 3) VAV flow; and
- 4) an operational time period which is run in parallel to the predicted/actual HVAC system’s operational time-period.

This energy-tempering device does have limitations which are relevant to the Glucksman Art Gallery benchmark for future qualification of performance. The ‘purchased air’ object *does not* facilitate the maintenance of RH conditions in the space. The system sizes the energy consumed by the unit based on space-temperature *alone*. The result is an unfair benchmark of minimum performance for calculating values of I_r . The zones serviced by AHU3 require strict temperature *and* RH control (Appendix A). In order to maintain adequate temperature and RH conditions in the space, outlet conditions for both purchased air objects servicing the two spaces must be configured uniquely¹⁰ (Table B-1). By configuring the model with these conditions, average RH conditions of 50% could be maintained throughout the month of July (Figure B-5).

Table B-1 – Nodal Purchase Air Outlet Conditions for each zone

Room	Purchased Air Outlet Node Condition	Units	Heating	Cooling
Media Room	Supply Air Temp	°C	30	16
	Supply Air Humidity Ratio	kg - H ₂ O/kg - air	0.0063	0.0063
Close Control	Room Supply Air Temp	°C	30	16
	Supply Air Humidity Ratio	kg - H ₂ O/kg - air	0.0066	0.0066

¹⁰ It is fully understood these outlet condition from the unit (zone inlet conditions) are unusual in the HVAC industry. The inability of EnergyPlus to size these units based on sensible and latent loads in the space mandated these inlet conditions. However these specifications do leverage the best qualification of minimum energy-use from the ‘purchased air’ object when strict RH control is required

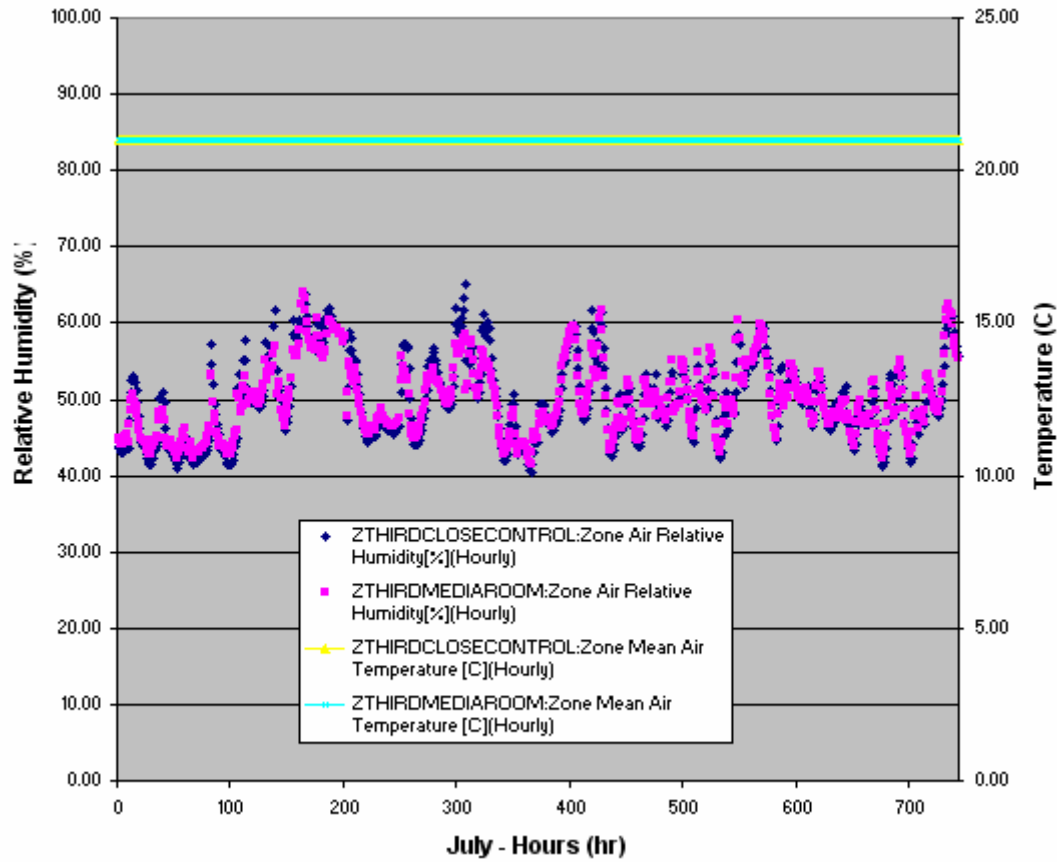


Figure B-5 – Average RH and temperature conditions in Media Room and Close Control Gallery over the month of July in the benchmark simulation¹¹

Another vital consideration for the BECs methodology are the thermal power loads leveraged from the benchmark model. The psychometric processes employed by EnergyPlus when calculating the Purchased Air objects' energy loads are wholly impractical for quantification of ideal performance of a real system (Figure B-6). In order to leverage a more rational representation of 'ideal' energy-use values from the benchmark model, more realistic schemes must be employed. Figure B-6 displays the psychometric nodal conditions (temperature, RH, moisture content, etc.) of air entering and leaving the 'Purchased Air' object on a psychometric chart (courtesy CIBSE, 1999).

¹¹ Note: the green line displayed in the figure is due to the blue colour mixing with the green colour. This line represents that internal climate control is being maintained at 21°C throughout the simulations

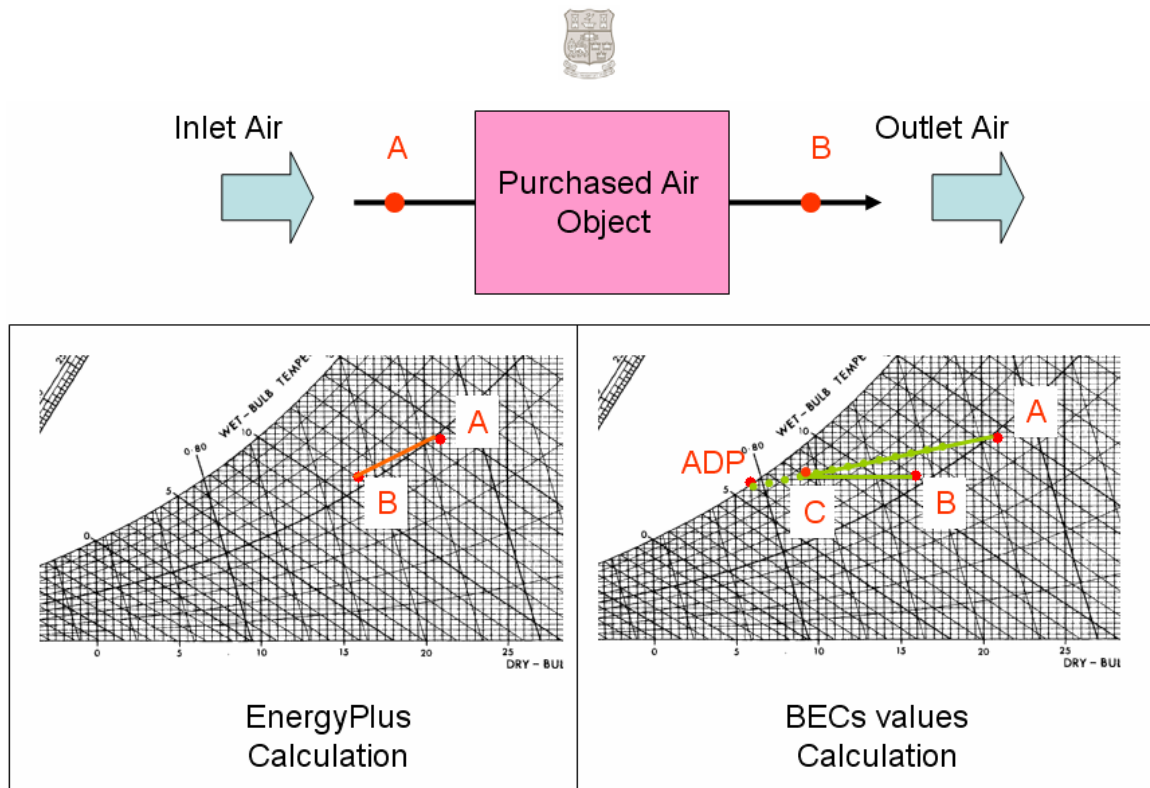


Figure B-6 – The mismatch in calculation schemes (between EnergyPlus and the BECs methodology) for energy required during the dehumidification season

During July’s dehumidification season (when the use of a cooling coil is required), the purchased air object moves along one process line for the EnergyPlus energy load calculation (A-B in Figure B-6). Accordingly, all energy load calculations for the Purchased Air object are calculated based on this practically-infeasible process line¹². However, a more realistic calculation is required for the BECs methodology.

During the dehumidification season, the use of a cooling coil and a reheat unit are required in order to move from ‘state A’ to ‘state B’. As seen in Figure B-6, nodal air conditions begin at ‘state A’ where a cooling coil is engaged (air is dehumidified and cooled) until it reaches ‘state C’ (an apparatus dew point (ADP) of 7°C is taken for the state that the cooling coil drives towards during the dehumidification process). Finally, air is reheated to ‘state B’ (the supply conditions for the zone).

¹² In reality, there are no HVAC components capable of tempering air in order to shift along this process line. Accordingly, they line may not be used to quantify the minimum energy required by a unit.



All cooling and heating energy loads are sized from the process lines delineated by the lines between A-C-B in Figure B-6. Data leveraged from the energy simulation model for AHU3 (Appendix C) are used throughout the BLC for generation of I_r values.

B.5.3 Alternative System Autosized Models

These whole building simulation models are configured with a fully autosized HVAC component description. Accordingly, they can be qualified as maximum efficiency *system-dependent* simulations of the buildings. Values leveraged from these models are employed for $I_{r(\text{early design})}$ during the alternative system selection phase (Section 3.2.1.1.1). For the purposes of highlighting the use of BECs values during the system selection phase of the BLC, two alternative HVAC systems were selected:

- 1) A constant volume HVAC system (Appendix D);
- 2) A Variable Air Volume (VAV) system (Appendix E).

Each of these HVAC systems are similarly configured (Figure B-7Figure 5-1). For the Glucksman Art Gallery, tight control of the temperature and RH conditions must be maintained in the space. Accordingly, both of these distinct AHUs have unusual AHU controls setpoint controls¹³. However, during the autosizing mode of operation, EnergyPlus is not sensitive to humidity controls. Accordingly, it is important to modify the sizing parameters for both simulation models in order to maintain a ‘best-fit’ of average temperature and RH space conditions (Appendix D; Appendix E). This requires iterative testing procedures for configuration of AHU outlet temperatures and moistures ratios during the heating and cooling time periods. These tests must run in parallel with the configuration of zone autosizing parameters until adequate levels of temperature and RH are maintained in the zone.

¹³ The main AHU unit (mixing box, cooling coil, humidifier and supply fan) maintain strict moisture ratio outlet conditions after the fan in order to ensure strict RH control in the spaces. This is unlike standard units which generally control terminal temperature conditions leaving the main unit of the AHU.

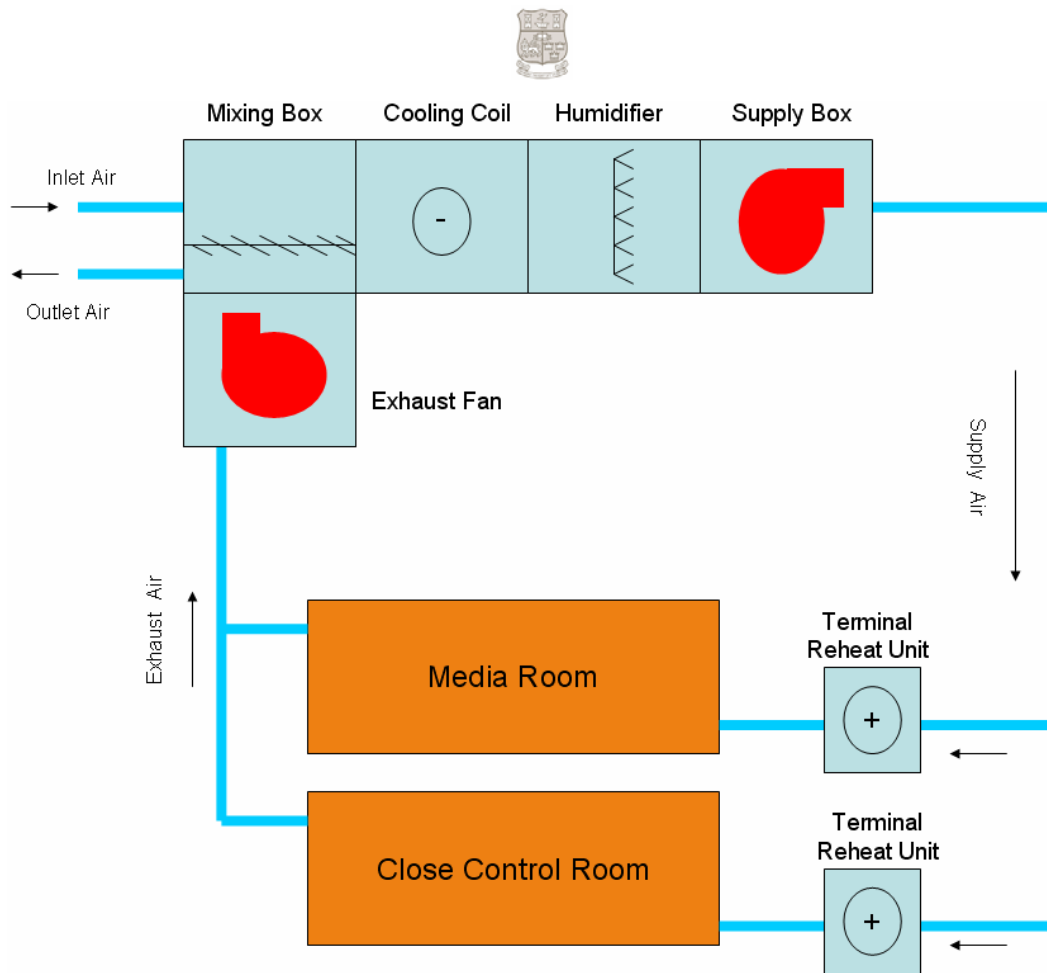


Figure B-7 – HVAC system configuration for constant volume and VAV systems

B.5.4 Detailed Design Phase

Two new models are generated during the detailed design phase:

- 1) an autosized system-dependent benchmark model; and
- 2) a detailed system-dependent simulation model.

The autosized system-dependent benchmark model predicts ideal performance for the HVAC system configuration employed in the building. However, it should be noted that this model is actually a copy of the model employed during the ‘system selection process’ (Section B.5.3). No alteration of the input file is required.

The detailed design simulation model predicts the performance of the system design by the HVAC design team. It accounts for the actual components employed by the system and offers the first view into the expected efficiency of the physical building and its energy systems during the operational phase.



The following two paragraphs discuss the two models used for the Glucksman Art Gallery's AHU3 during the detailed design stages.

B.5.5 Autosized System Benchmark

As discussed in Section 5.3.1.1, the 'VAV HVAC system' is chosen as values of I_r highlight this system configuration's superior efficiency potential. Accordingly, data leveraged from the VAV autosized simulation model discussed in Section B.5.3 are employed to represent these benchmark values (Appendix E).

B.5.6 Detailed Design Simulation Model

The next generation of the energy simulation models in the BECs methodology may be developed as system component data become available from manufacturer's catalogues, mechanical design schematics, etc. All process variables, which were previously 'autosized', are replaced with predicted values (e.g. air flow rates, temperature set points, etc.). Accordingly, a more accurate prediction of operational energy-use is generated.

For the Glucksman Art Gallery, the simulation model was initially configured with process variables value inputs directly from the catalogue data specifications. However, a simplification of this model was required in order to leverage data sets for BECs value calculations. Configuration of the component's design specifications was unworkable:

- 1) AHU3 operates under three distinct modes of operation. These are referred to as 'fully-on' (air flow of $0.86\text{m}^3/\text{s}$), 'half-operation' (air flow of $0.45\text{m}^3/\text{s}$) and 'fully-off' (air flow of $0.0\text{m}^3/\text{s}$). Currently, EnergyPlus does not facilitate the simulation of this form of 'stepped' operation. The simulation of a VAV system in EnergyPlus offers the 'closest fit' possible by setting a maximum and minimum air flow rates for the AHU. However, during the VAV simulation runs, EnergyPlus automatically employs the 'minimum' flow rate. Accordingly the system thermal power rates are undersized as actual flow rates during normal operation hours are 'full-on'. To account for these operations in the physical AHU3, the maximum flow rate is set to the 'fully-on' conditions ($0.86\text{m}^3/\text{s}$) while the minimum flow rate is set to half way between 'fully-on' and 'half-operation' ($0.66\text{m}^3/\text{s}$).



- 2) During maximum flow operation, the spaces serviced by AHU3 are supplied with $0.86\text{m}^3/\text{s}$ of tempered air. However, only $0.45\text{m}^3/\text{s}$ of air is exhausted from the areas (the remaining portion of air is filtered out into the hallway). EnergyPlus is currently unable to simulate this form of HVAC system configuration due to restrictions intrinsically tied to the internal mass balance calculations for HVAC systems (US-DOE 2005). Accordingly, the supply and exhaust fans are configured similarly (the maximum and minimum flow rates are set to the same value).
- 3) When the simulation model is configured with design data, the current version of EnergyPlus is unable to manage adequate control of the HVAC system that manages strict relative humidity in the spaces. This results in inaccurate thermal power calculations for the cooling coils and the space reheaters. Simplification of the simulation's process variables and set points was required in order to operate successful space conditions.

These issues are mirrored for each subsequent simulation model employed by the BECs methodology. Accordingly, all yardsticks of energy efficiency for the building are not considered to provide final qualification of performance. They merely serve to display the processes and output offered by the BECs methodology¹⁴.

The final detailed model was configured to display the use of energy simulation models during this phase of the BLC (Appendix F). All data leveraged from the model are used for I_r calculations (Section 5.3.1.2).

B.5.7 Commissioning Phase

An additional model is generated after the commissioning phase of the BLC. It is a system-dependent energy simulation model configured with commissioning process flow variable data.

This detailed simulation model predicts the operational performance system. It accounts for the any variation from the design specification that may be encountered after the

¹⁴ It is envisaged that the simulation engine employed by EnergyPlus will reach a degree of maturity in the future which will facilitate a more trustworthy assessment of performance.



HVAC system has been installed. Air and water flow rates variations recorded during the commissioned tests may be configured in the energy simulation model. Accordingly, it offers a superior prediction of performance.

The following subsection discusses the models used for the Glucksman Art Gallery's AHU3 after the commissioning phase of the BLC.

B.5.8 Commissioning Simulation Model

The data sets gathered during the commissioning tests did not alter from the design specifications. All process flow variables were similar and the operations set points were remained the same. Accordingly, the energy simulation model employed during for commissioning stages (Appendix E) is identical to the detailed design model configuration (Section B.5.6).

B.5.9 Operations Stage

One new energy simulation model is configured and one new data repository is employed during the operations phase of the BLC:

- 1) a calibrated system-dependent energy simulation model configured from operational data; and
- 2) HVAC process flow data leveraged the BMS.

The calibrated energy simulation model of AHU3 predicts the ideal performance of the system when it is operating as specified by the design team.

Data leveraged from the BMS generates a view of the energy used by AHU3 under normal operation.

B.5.10 Fully Calibrated Simulation Model

Due to the integrity issues related to the BMS data, it was not possible to adequately calibrate the energy simulation model for AHU3. Accordingly, the energy simulation model employed to represent a fully calibrated simulation model of AHU3 (Appendix G) is identical to the detailed design model configuration (Section B.5.6).



B.5.11 BMS Data

AHU3 is considered to be adequately sensed. However, on close examination of the process flow conditions, the data set were deemed to be lacking in the integrity and reliability required for evaluation using the BECs methodology. Accordingly, this research was unable to access trustworthy data for each of the systems in AHU3 for evaluation of performance using BECs values. However, a data set displaying the thermal power use for the cooling coil over a three day period in July was manually assessed and validated. Accordingly, these data adequately representing real operation and could be employed during an evaluation of cooling coil performance (Appendix F).



Appendix C Benchmark Energy Simulation Model

See CD

Appendix D Autosized CV Energy Simulation Model

See CD

Appendix E Autosized VAV Energy Simulation Model and Data

See CD

Appendix F Detailed VAV Energy Simulation Model and Data

See CD

Appendix G Commissioned VAV Energy Simulation Model and Data

See CD

Appendix H BMS Data

See CD

Appendix I Calibrated VAV Energy Simulation Model and Data

See CD



Appendix J Calculations BECs values throughout the BLC

See CD

Appendix K IFC-based BIM of Glucksman Art Gallery

See CD





References

- ANSI/ASHRAE (1999). Standard 105-1984 (RA99), Standard Methods of Measuring and Expressing Building Energy Performance, American Society of Heating, Refrigeration, and Air-Conditioning Engineers, Washington DC.
- ASCE (2004). Sustainable Engineering Practice, ASCE Publications. ISBN 0784407509.
- Asimakopoulous, D. N., V. D. Assimakopoulos, Chrisomallidou, N., Klitsikas N., Mangold, D., Michel, P., Santamouris, M., Tasangrassoulis, A. (2001). Energy and Climate in the Urban Built Environment, James & James/Earthscan, ISBN 1873936907.
- Augenbroe, G. (2002). "Trends in building simulation." Building and Environment **37**(8-9): PP 891-902.
- Autodesk (2002). Building Information Modeling White Paper, Autodesk Ink., San Rafael, CA, USA, available online at http://www.laiserin.com/features/bim/autodesk_bim.pdf.
- B&E (2006). Building And Estates Office, University College Cork (UCC), Cork, Ireland.
- Bazjanac, V. (2001). Acquisition of Building Geometry in the Simulation of Energy Performance. Building Simulation 2001, Rio de Janeiro, Brazil.
- Bazjanac, V. (2003). Improving Building Energy Performance Simulation with Software Interoperability. Building Simulation 2003, Eindhoven, Netherlands.
- Bazjanac, V. (2004). "Building energy performance simulation as part of interoperable software environments." Building and Environment **39**: 879-883.
- Bazjanac, V., F. Grobler, A.T. Shaw (2006). Implementation of IFC-based Building Information Modelling, GSA. US General Services Administration Public Buildings Service.
- Beller, D., G. Foliente, B. Meacham. (2001). Qualitative Versus Quantitative Aspects of performance-Based Regulations. Proceedings CIB World Congress, Wellington, NZ, CIB 2001.
- Bentley (2003). Does the Building Industry Really Need to Start Over - A response from Bentley to Autodesk's BIM/Revit Proposal for the Future, Bentley, available online at http://www.bentley.com/files/industry_groups/building/BIM_white_paper.pdf.



Bergeron, D. and B. Bowen (2001). Acceptable Solutions. CIB World Building Congress, Wellington, New Zealand.

Best, R. and G. d. Valence (1999). Building in Value, Butterworth-Heinemann. ISBN: 0340741600.

Best, R., G. d. Valence, C. Langston. (2003). Workplace Strategies and Facilities Management: Building in Value, Elsevier.

BLIS (2000). Building Lifecycle Interoperable Software, <http://www.blis-project.org>.

BREEAM (2005). BREEAM: BRE Environmental Assessment Method, <http://www.breeam.org/>.

Brochner, J., G. K. I. Ang, G. Fredriksson. (1999). "Sustainability and the performance concept: encouraging innovative environmental technology in construction." Building Research & Information **27**(6): 367-372.

CalArch (2005). California Building Energy Reference Tool, EETD, Lawrence Berkeley National Laboratory. <http://poet.lbl.gov/cal-arch/contact.html>.

Canbay, C. S., A. Hepbasli, G. Gokcen. (2004). "Evaluating Performance Indices of a shopping centre and implementing HVAC Control Principles to Minimise Energy Usage." Energy and Buildings **36**: 587-598.

Carnevale, D. G. (1992). "Physical Settings of Work." Public Productivity and Management Review **15**(4): 423-436.

CEC (2003). Impact Analysis for Residential and Non-Residential Buildings, 2005 Update to the California Energy Efficiency Standards. E. Associates, California Energy Commission.

Chappell, D., D. Marshall, V. Powell-Smith, S. Cavender. (2001). Building Contract Dictionary, Blackwell Publishing. ISBN 0632039647.

Chau, C. K., W. L. Lee, F.W.H. Yik, J. Burnett. (2000). "Towards a successful voluntary building environmental assessment scheme." Construction Management & Economics **18**(8): 959 - 968.

CIB (1953). International Council for Research and Innovation in Building and Construction (CIB). www.cibworld.nl. **2005**.

CIB (1997). Final Report of CIB Task Group 11: Performance-based Building Codes, International Council for Research and Innovation, Studies and Documentation (CIB), Rotterdam, Netherlands.



CIBSE (1999). Environmental Design CIBSE Guide A, Yale Press Ltd.

Claridge, D., J. Haberl, M. Liu, J. Houcek, A. Athar. (1994). Can You Achieve 150% Predicted Retrofit Savings? Is it Time for Re-Commissioning. ACEEE 1994 Summer Study on Energy Efficiency in Buildings, American Council for and Energy Efficient Economy.

Clarke, J. (2001). Energy Simulation in Building Design, Elsevier. ISBN 0750650826.

Clements-Croome, D. (1997). Specifying Indoor Climate in Naturally Ventilated Buildings, Londong: Spon (Chapman and Hall).

Clements-Croome, D. (2000). Creating the Productive Workplace, Spon Press (UK).

Clements-Croome, D. (2003). Better buildings, better business. Building Services Journal. **11/03**: P44-46.

Clements-Croome, D. (2004). Intelligent Buildings, Thomas Telford. ISBN 0727732668.

Cole, R. J. (1999). "Building environmental assessment methods: clarifying intentions." Building Research & Information **27**(4): 230-246.

Cole, R. J. (2001). "Lessons learned, future directions and issues for GBC." Building Research & Information **29**(5): 355-373.

Cole, R. J. (2002). Review of GBTool and Analysis of GBC 2002 Case-Study Projects, Buildings Group/CETC, Ottawa, Canada.

Council, E. R. E. (2004). Renewable Energy in Europe, James & James/Earthscan.

Crimson-Editor (2005). Crimson Editor, <http://www.crimsoneditor.com/>.

Davidson, P. (2005). Easy does it. Building Services Journal. **06/05**: 12-13.

Dix, T. (2003). Time to deliver. Building Services Journal. **11/03**: P37-38.

Economist (2006). Calculating the costs of pricey oil. The Economist Agenda. **April 28th**.

Ellis, M. W. and E. H. Mathews (2002). "Needs and trends in building and HVAC system design tools." Building and Environment **37**(5): 461-470.

Emmitt, S., L. A. Jacobs, C. Gorse. (2003). Construction Communication, Blackwell Publishing.



Emmitt, S. and D. T. Yeomans (2001). Specifying Buildings, Elsevier. ISBN: 075064849X.

Espedokken, K. (2006). IDM Methodology - Information Delivery Manual, <http://idm.buildingsmart.no/confluence/display/IDM/Home>.

ESP-r (2006). Integrated Modelling tool for the simulation of building performance; ESP-r, <http://www.esru.strath.ac.uk/Programs/ESP-r.htm>.

EU (2000). Towards a European Strategy for Energy Supply, European Commission.

EU (2003a). Directive 2003/87/EC of the European Parliament and of the council of 13 October 2003 establishing a scheme for greenhouse gas emission allowance trading within the Community and amending Council Directive 96/61/EC, European Union.

Evans, R., R. Haryott, N. Haste, A. Jones. (1998). The long-term costs of owning and using buildings, The Royal Academy of Engineering.

Fahey, A. (1994). Collections Management, Routledge (UK).

Federspiel, C., Q. Zhang, E. Arens. (2002). "Model-based benchmarking with application to laboratory buildings." Energy and Buildings **34**(3): 203-214.

Fine, T. L. (1999). Feedforward Neural Network Methodology, Springer. ISBN 0387987452.

Fletcher, K. (2004). Kyoto rocks.... Building Services Journal. **01/04**: pp10.

Foliente, G. C. and R. Becker (2001). CIB PBBCS Proactive Programme - Task 1. Compendium of Building Performance Models., CSIRO Building, Construction and Engineering, Victoria, Australia.

Gallaher, M. P., A. C. O'Connor, J.L. Dettbarn Jr, L.T. Gilday.. (2004). Cost Analysis of Inadequate Interoperability in the U.S. Capital Facilities Industry, National Institute of Standards and Technology (NIST), Gaithersburg, MD.

Garbutt, J. (2003). Cover up for energy efficiency. Building Services Journal. **11/03**: P53-54.

Gaterell, M. R. and M. E. McEvoy (2004). "The impact of climate change uncertainties on the performance of energy efficiency measures applied to dwellings." Energy and Buildings **37**: 982-995.

GBC (2005). Green Building Challenge 2005, <http://www.iisbe.org/iisbe/gbc2k5/gbc2k5-start.htm>.



gbXML (2006). Green Building XML. A Building Information Modelling Solution for our Green World, <http://www.gbxml.org/>.

Geller, H. (2002). Energy Revolution, Island Press.

Gordon, G. (1969). System Simulation, Prentice-Hall International.

Graphisoft (2003). The Building Information Model: A Look at Graphisoft's Virtual Building Concept, Whitepaper, Cyon Research Corporation, available online at <http://www.cadwire.net/to?graphisoft/wp/virtualbuilding>.

Gratia, E. and A. D. Herde (2002). "Design of low energy office buildings." Energy and Buildings **35**: 473-491.

Grimm, N. R. and R. C. Rosaler (1997). HVAC Systems and Components Handbook, McGraw-Hill Professional.

Herzog, P. and L. LaVine (1992). Identification and quantification of the impact of improper operation of midsize Minnesota office buildings on energy use: a seven building case study. ACEEE 1992 Summer Study on Energy Efficiency in Buildings, American Council for and Energy Efficient Economy.

Hitchcock, R., M. A. Piette, S. Selkowitz. (1998). Performance Metrics and Life-Cycle Information Management for Building Performance Assurance. ACEE '98 Summer Study on Energy Efficiency in Buildings, Pacific Grove, CA, USA.

Hitchcock, R. J. (2002). Metracker: A Tool for Tracking Performance Metrics over Time.

Hitchcock, R. J. (2003). "Standardized Building Performance Metrics" LBNL Technical Report for CEC PIER High Performance Commercial Building Systems Program, LBNL Report No. 53072.

Höschele, K. (1991). "How to meet an increasing concern of citizens in a city climate." Energy and Buildings **15**: 11-14.

Howley, M., F. O'Leary, B. O'Gallachoir. (2006). Energy in Ireland 1990 - 2004. Trends, issues, forecasts and indicators, Sustainable Energy Ireland (SEI).

HPCBS (2005). High Performance Commercial Building Systems, U.S. Department of Energy's Lawrence Berkeley National Laboratory. <http://buildings.lbl.gov/hpcbs/>.

Hui, S. C. M. (2002). Environmental Sustainability Assessment of Buildings Using Requirements in Building Energy Codes. Sustainable Building 2002 International Conference, Oslo, Norway.



Hui, S. C. M. (2003). Energy Efficiency and Environmental Assessment for Buildings in Hong Kong. Advances on Energy Efficiency and Sustainability in Buildings, Kuala Lumpur, Malaysia.

IAI (1995). International Alliance for Interoperability, <http://www.iai-international.org/>.

IAI (2006). buildingSMART. IFC2x Edition 3, final documentation available at http://www.iai-international.org/Model/R2x3_final/index.htm.

Ibrahim, M., R. Krawczyk, G. Schipporeit. (2004). Two Approaches to BIM: A Comparative Study. Education in Computer Aided Architectural Design in Europe, eCAADe 2004 Conference, Copenhagen, Denmark.

IES (2006). Building Performance Analysis Tools; IESVE, <http://www.iesve.com>.

Jones, P. and H. Davies (2003). Bridging the great divide. Building Services Journal. **11/03**: P41-42.

Karola, A., H. Lahtela, R. Hanninen, R. Hitchcock, Q. Chen, S. Kajka, K Hagstrom. (2002). "BSPro Com-Server -- interoperability between software tools using industry foundation classes." Energy and Buildings **34**: 901-907.

Karwowski, W. and W. S. Marras (1998). The Occupational Ergonomics Handbook, CRC Press.

Kennett, S. (2005). Tall Story. Building Services Journal. **05/05**: PP24-28.

Kinney, C. and N. Soubiran (2004). "Interactive Roadmap to Conceptual Cost Estimating." AACE International Transactions **46**(9).

Kiviniemi, A. (2006). Construction Operations Building Information Exchange, a national project to streamline O&M information handoff, <http://www.bfrl.nist.gov/PSSIWG/presentations/COBIE1.pdf>.

Langston, C. (2001). Sustainable Practices in the Built Environment, Butterworth-Heinemann, Oxford. ISBN: 0-7506-5153-9.

Langston, C. and R. Lauge-Kristensen (2002). Strategic Management of Built Facilities, Elsevier. ISBN 0750654406.

Lee, W. L. and F. W. H. Yik (2002). "Regulatory and voluntary approaches for enhancing energy efficiencies of buildings in Hong Kong." Applied Energy **71**(4): 251-274.

LEED (2005). Leadership in Energy and Environmental Design (LEED), US Green Building Council. <http://www.usgbc.org/>.



- Lenschow, A. (2001). Environmental Policy Integration, James & James/Earthscan.
- Maguire, M., C. (1985). A Review of Human Factors Guidelines and Techniques for the Design of Graphical Human - Computer Interfaces, HUSAT Research Center, Loughborough University, UK: pp161-84.
- Mahling, D. E. and K. Lehman (2005). Enterprise Energy Management. HPAC Engineering. **77**: PP 40-42.
- Mason, H. (2002). ISO 10303 - STEP - A key standard for the global market, ISO Bulletin, January 2002.
<http://www.iso.ch/iso/en/commcentre/isobulletin/articles/2002/pdf/step02-04.pdf>.
- Morrissey, E., M. Keane, J. O'Donnell, J. McCarthy. (2005a). Building Effectiveness Ratios for improved Building Life Cycle Management. IBPSA Building Simulation 2005, Montreal, Canada.
- Morrissey, E. D. (2005). EArchive - A tool for capturing design and operations intent for buildings, IRUSE. Available at www.ucc.ie/iruse/EArchive.html.
- Mourshed, M. M., D. Kelliher, M. Keane. (2003). Integrating building energy simulation in the design process. IBPSA News. **13**: 21-26.
- Neuberg, F., C. Ekkerlein, E. Rank, M. Faulstich. (2004). Integrated Life Cycle Simulation and Assessment of Buildings. International Conference on Computing in Civil and Building Engineering, ICCCBE, Weimar , Bauhaus-Universität.
- NIBS (2006). The National Institute of Building Sciences, The U.S. National CAD Standard Project Committee, <http://www.nibs.org/>.
- OAG (2005). The Office of the Attorney General, <http://www.irishstatutebook.ie/>.
- ODPM (2005). Office of the Deputy Prime Minister, www.odpm.gov.uk.
- OECD (2003). Environmentally Sustainable Buildings: Challenges and Policies, Organisation for Economic Co-operation and Development.
- O'Sullivan, D., M. Keane, D. Kelliher, R.J. Hitchcock. (2004). "Improving building operation by tracking performance metrics throughout the building lifecycle (BLC)." Energy and Buildings **36**(11): 1075-1090.
- Pang, P. N. T. (2003). The Essentials of Quality Control Management, Trafford Publishing.



- Papamichael, K., J. La Porta, H. Chauvet. (1997). Decision-Making through use of multiple interoperable simulation software. Building Simulation '97, Prague, Czech Republic.
- Papamichael, K. and V. Pal (2002). Barriers in developing and using simulation-based decision-support software, Lawrence Berkeley National Laboratory, LBNL-50515.
- Pearson, A. (2005). States tackle emissions. Building Services Journal. **09/05**: pp9.
- Petroski, H. (1994). Design Paradigms, Cambridge University Press.
- Piggott, J. (2004). From buildings to business facilities. Building Services Journal. **02/04**: 33-34.
- Prazeres, L. and J. A. Clarke (2003). Communicating Building Simulation Outputs To Users. Building Simulation 2003, Eindhoven, Netherlands.
- Preiser, W. and E. Ostroff (2001). Universal Design Handbook, McGraw-Hill Professional. ISBN 0071376054.
- Romberg, R., A. Niggel, R. Ernst. (2004). Structural Analysis based on the Product Model Standard IFC. Proceedings of 10th International Conference on Computing in Civil and Building Engineering (ICCCBE), Weimar.
- Rousseau, P. G. and E. H. Mathews (2003). "Needs and trends in integrated building and HVAC thermal design tools." Building and Environment **28**(4): PP 439-452.
- Salsbury, T. I. and R. C. Diamond (2001). "Fault detection in HVAC systems using model-based feedforward control." Energy and Buildings **33**: PP 403-415.
- Santamouris, M. (2004). Solar Thermal Technologies for Buildings, James & James/Earthscan.
- SEI (2005). Action Plan for Implementation of the EU Energy Performance of Buildings Directive in Ireland, EPBD Working Group, Sustainable Energy Ireland. www.epbd.ie.
- Selkowitz, S., M. A. Piette, K. Papamichael, D. Sartor, R. Hitchcock, F. Olken. (1996). Interoperable, Life-cycle Tools for Assuring Building Performance: An Overview of a Commercial Building Initiative. U.S. Green Building Council Third Annual Conference, San Diego, CA, USA.
- Solibri (2005). Solibri Model Checker, <http://www.solibri.com/services/public/main/main.php>.



Thompson, J. (1997). Can commissioning Impact Professional Liability Claims Made Against Architects and Consulting Engineers? Fifth National Conference on Building Commissioning, Long Beach, CA, USA.

Title24 (2006). Title 24, PART 6 - California's Energy Efficiency Standards for Residential and NonResidential, <http://www.energy.ca.gov/title24/>.

Treeck, C. v., R. Romberg, E. Rank. (2003). Simulation based on the product model standard IFC. Building Simulation 2003, Eindhoven, Netherlands.

Tubbs, B. (2003). "Performance Based Building" Domain 7: Regulations, Report, Performance Based Building Thematic Network (PeBBu).

Tufte, E., R. (1990). Envisioning Information, Graphic Press, Cheshire, Connecticut.

Tullis, T. S. (1988). Screen Design. Handbook of Human-computer Interaction. H. M, North-Holland: P377.

Turner, W. C. (2004). Energy Management Handbook, CRC Press. ISBN 0824748123.

UK-Government (2003). Energy White Paper: Our Energy Future-Creating a Low Carbon Economy, The Stationary Office, Norwich: p142.

US-DOE (2005). EnergyPlus Energy Simulation Software, U.S. Department of Energy. <http://www.eere.energy.gov/buildings/energyplus/>.

Wallace, D. (1995). Environmental Policy and Industrial Innovation, James & James/Earthscan.

Warwick, K., G. W. Irwin, K.J. Hunt, D. Atherton, S. Spurgeon. (1995). Neural Network Applications in Control, IET. ISBN 0852968523.

Wells, J. (2002). Solutions for Energy Security and Facility Management Challenges, Marcel Dekker.

Wilde, P. d., G. Augenbroe, M. van der Voorden. (2002). Energy system simulation in performance-based building design. 6th International Conference on System Simulation in Buildings 2002, Liège, Belgium.

Williams, B. (2000). An Introduction to Benchmarking Facilities and Justifying the Investment in Facilities, IFPI Limited.

Zimmermann, M., H.-J. Althaus, A. Haas. (2005). "Benchmarks for sustainable construction. A contribution to develop a standard." Energy and Buildings **37**(11): 1147-1157.

