Department of Mechanical and Aerospace Engineering

An Investigation into the Requirements for Future Simulation Capabilities of Commercial Building Modelling Tools

Author: James Sweeny

Supervisor: Professor Joe Clarke

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Copyright Declaration

This thesis is the result of the author's original research. It has been composed by the author and has not been previously submitted for examination which has led to the award of a degree.

Signed: James Sweeny   Date: 6th September 2014

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Abstract

Commercial building performance modelling tools have been widely used in the UK for many years and provide a powerful and cost-effective way of addressing the complexities underlying building design. However, as the technologies associated with building design evolve and become more arbitrarily complex, there is a requirement within industry for the functionality of commercial codes to follow suit. This project addresses the future functionality of existing commercial tools for building simulation. It uses a conjecture and test approach whereby the performance appraisal requirements of practitioners are conjectured on the basis of interviews with industry professionals and tested by exercising a selection of commercially available tools. The thesis aims to elaborate and specify the functionality that will be required in the development of commercial simulation codes to ensure they align with practitioners' expectations and future design requirements. Deficiencies then observed give rise to the identification of new functionality that will be required of future commercial tools to ensure that they align with the rapidly evolving practitioner requirements. Areas that have been considered include health and wellbeing of occupants, complex constructional systems, time adaptive material behaviour (such as phase change materials and green roofs), community district heating systems, active demand management and many other domains. Through commercial tool evaluation, the project provides a requirements specification for future commercial tool refinement

Acronyms

ANSI:	American Nation Standards Institute
ASHRAE:	American Society of Heating, Refrigeration and Air Conditioning Engineers
BATS:	Biosphere Atmosphere Transfer Scheme
BIPV:	Building Integrated Photovoltaics
BREEAM:	Buildings Research Establishment Energy Assessment Method
BRUKL:	Building Regulation United Kingdom Part L
CBECS:	Commercial Building Energy Consumption Survey
CFD:	Computational Fluid Dynamics
CHP:	Combined Heat and Power
CIBSE:	Chartered Institute of Building Services Engineers
CIE:	International Commission on Illumination
COP:	Coefficient of Performance
CRI:	Colour Rendering Index
DGI:	Daylight Glare Index
DGP:	Daylight Glare Probability
EPC:	Energy Performance Certificate
FAAST:	Fast All Season Soil Strength
HVAC:	Heating, Ventilation and Air Conditioning
I^2PV:	Integrated and Interactive Performance View
IAQ:	Indoor Air Quality
IES:	Integrated Environment Solutions
IPCC:	International Panel for Climate Change
ISO:	International Standards Organisation
LEA:	Leaf Area Index
LED:	Light Emitting Diode
LEED:	Leadership in Energy and Environmental Design
LV:	Low Voltage
NINES:	Northern Isles New Energy Solutions
NR:	Noise Rating
PAM:	Performance Assessment Method
PC:	Personal Computer
PCM:	Phase Change Materials
PMV:	Percentage Mean Vote
PPD:	Percentage of People Dissatisfied
RFM:	Response Factor Method
SBEM:	Simplified Building Energy Modelling
SiB:	Simple Biosphere Model
SRI:	Solar Reflective Index
TAS:	Thermal Analysis Simulation
UGP:	Unified Glare Rating
USGBC:	US Green Building Council
VCP:	Visual Comfort Probability

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1. Project background & method

It is generally accepted that the world is complex. It is complex in the way that it operates and the way that it affects the environment, which surrounds it. There have been many debates and discussions as to how the planet behaves and will behave in the future. One of the main topics that has driven many debate amongst scientists, politicians and engineers alike, is the concept of anthropogenic climate change. The most recent IPCC report claims that scientists are 95% certain that humans are the "dominant cause" of global warming since the 1950s (IPCC, 2013), and this has resulted in a great deal of concern amongst society. Furthermore, the Kyoto Protocol was introduced in 1990 (United Nations, 1998) and resulted in CO_2 target reduction commitments, of which many countries, including the UK, have signed up to. Indeed, it has driven most government policies and affected behaviours amongst the general public.

Buildings typically account for 43% of the CO_2 emissions within the UK (Department for Communities and Local Government, 2014). Within the building sector as a result of these discussions, policy makers have driven the agenda of reducing carbon by ensuring sustainable communities are low carbon and environmentally friendly in order to help meet these targets. This has given rise to UK government incentives such as energy performance certificates, the green deal and the code for sustainable homes. Building simulation offers the construction industry the opportunity to address thermodynamic complexities and undertake integrated performance appraisals of options at reasonable cost; however there are many challenges associated with applying this technology in practice.

1.1. Emergence of building performance modelling

The foundations behind building performance simulation can be traced as far back as 1925 when Nessi and Nisolle used Response Factor Methods (RFM's) to calculate transient heat flow (Nessi, et al., 1925). The '60s brought about the first computer simulation to carry out air conditioning calculations. In the seventies, due to the major oil crisis, the simulation process evolved further giving more emphasis to the environmental aspects of building performance, and by the '90s due to the rise of the PC, the first commercial tool was made readily available to the general public (IBPSA-USA, 2012). It can be observed that throughout history, building simulation has evolved considerably. In today's society, the emergence of the Building Energy Performance Directive (The European Parliament and The Council of the European Union, 2002), which promotes the improvement of energy performance of buildings in the EU, and the release of ASHRAE 90.1 energy modelling (ANSI/ASHRAE/IES, 2013) in accordance with LEED guidelines (USGBC, 2014), has given further impetus to the use of energy modelling in building simulation. It is of no surprise that practitioners are now using this method more routinely to assess building performance. For this reason building energy simulation is a crucial tool that aims to match the expectations of the modern day practitioner and it is envisaged that building simulation tools will continue to grow and develop in the years to come to fulfil this evolving need.

Commercial codes have been widely used in the industry for many years and are powerful and time-effective ways of modelling some of the complexities involved with building simulation. However, as the technologies associated with building design evolve and become more arbitrarily complex, there emerges a requirement within industry for the functionality of commercial codes to follow suit. It is reasonable to deduce that in terms of accuracy and precision, there is still a long way to go when developing these tools to represent real systems explicitly. Some of the future requirements of the functionality required for commercial building simulation codes already exist within academic/specialist research codes and so the gap between these programs should be expected to narrow over time.

As may be expected, commercial code vendors report a high degree of sophistication in the capabilities their tools can deliver and scenarios that they can address. However, it may be reasonably expected that in some areas commercial programs will be found to be lacking. There are various programs that are available to the industry globally, however for the purposes of this investigation only those commercial programs available to UK practitioners are considered.

The four main commercial codes that have been considered for this investigation are listed as follows:

1.) IES VE;
2.) EDSL TAS;
3.) Bentley Hevacomp;
4.) Design Builder.

Commercial vendors often promote their tools against the vision of requirements of practitioners; in the case of IES for example, the tool is described as being an

"innovative, award-winning, and in-depth suite of integrated analysis tools"

and is expressed as being able to

> *"test different design options, identify best passive solutions, compare low carbon technologies, and draw conclusions on energy use, CO_2 emissions, occupant comfort, light levels, airflow, Part L, BREEAM, LEED, EPC Ratings, and much more."*

Figure 1 gives an example as to the complex geometries and shading that can be carried out for a large building and also depicts some of the CFD capabilities for examining external wind patterns in relation to the building. Figure 2 depicts an output of luminance distribution within a typical space as well as air flow characteristics.

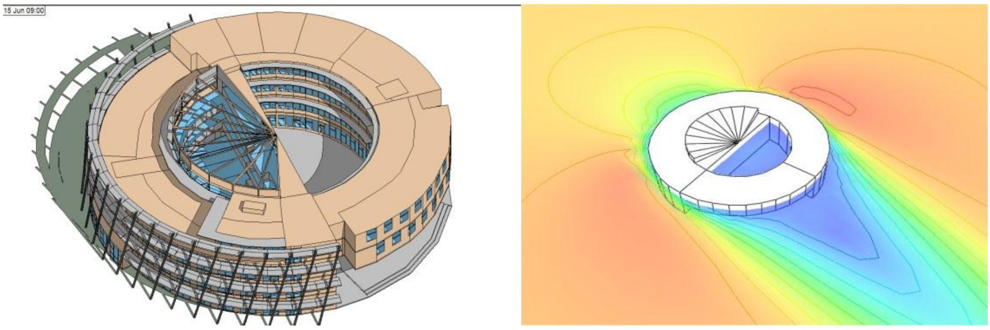

Figure 1 IES modelling & CFD capabilities (IES VE, 2014)

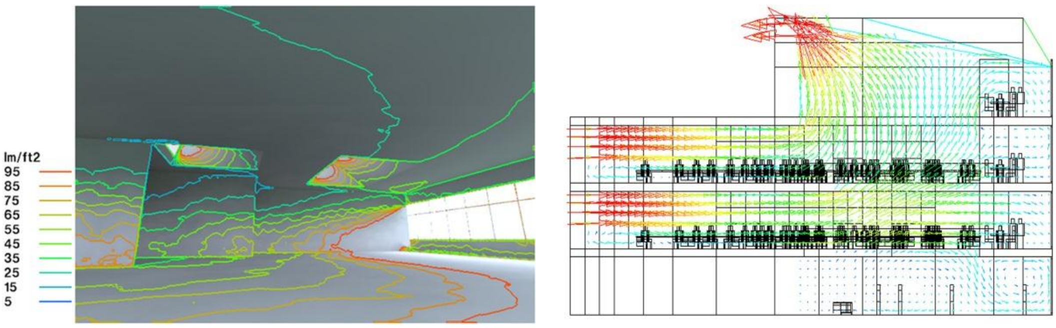

Figure 2 Typical IES output of luminance and airflow (IES VE, 2014)

In the case of TAS the tool is described as being *"a complete solution for thermal simulation of new or existing buildings"* expressed as being capable of;

"Performing dynamic thermal simulation of the world's largest and most complex buildings, TAS allows designers to accurately predict energy consumption, CO2 emissions operating costs and occupant comfort."

Figure 3 represents some of the information that can be drawn out of simulation in relation to the distribution of energy consumption from lighting to room heating consumption as well as CO_2 emissions. Figure 4 represents typical regulations compliance that the TAS simulation tool can offer practitioners, with BRUKL output reports and EPC certificates to ensure buildings meet the requirements of Part L regulations.

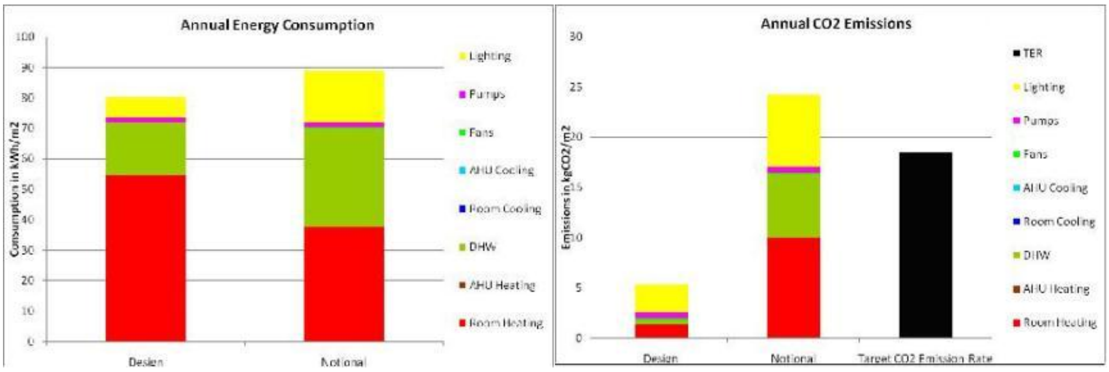

Figure 3 Typical TAS simulation outputs (EDSL TAS, 2012)

Figure 4 Typical TAS model and certification compliance (EDSL TAS, 2012)

Overall, it can be concluded that vendors claim that the tools are integrative in covering most aspects of building performance, have the ability to predict occupant comfort and energy consumption, interoperable with most other file formats and much more. The first part of this thesis identifies a complete list of these claims, which are shown in Appendix B.

1.2. Project aims & method

There is a physical reality of building performance that needs to be represented in a simulation program and all commercial programs are in a sense 'hybrid' formulations, e.g. in some regards commercial codes might deal well with representing reality, in other regards they might adopt a simplified engineering calculation, or they might simply be unable to model aspects of building performance. Commercial vendors make a series of claims, and in some cases these are grossly overstated: indeed there are still many things the tools cannot yet achieve. This thesis aims to elaborate and specify the functionality that will be required in the development of commercial simulation codes both now and in the future to ensure they align with practitioner's expectations and requirements.

It is important to establish a complete definition of what building simulation is in order to address the future requirements of where it needs to evolve. Simulation is not simply a group of mathematical calculations; for the present purpose it is defined as a method to emulate reality in a way that can be confirmed by observation.

In order to investigate and test the modelling capabilities of commercial codes with buildings of arbitrary complexity, a target of reality must be defined to compare the claims of commercial codes against. Indeed an integrated view of performance goes far beyond the notion of how much carbon emissions a building emits – it is complex in nature, it is ambitious and has been defined based on the literature review, lectures, interviews, and experiences of the author.

Target of reality

All real buildings are complex in nature because of four essential characteristics: they are:

1.) Dynamic;
2.) Non-Linear;
3.) Systemic;
4.) Stochastic.

They are dynamic due to the fact that the systems and processes are constantly changing. They are non-linear because the parameters vary with the state-variables, e.g. there is no such thing as a fixed air change rate, U-value, or plant efficiency factor. Such impositions are crude abstractions of the real world and the parameters associated with these elements are dependent on the solution and unknown to the tool user at the time of problem definition. Such constructs do not take into account the non-linearity of building performance and can substantially affect the accuracy of the simulation results.

Buildings are systemic due to the fact that there are lots of domains associated with building performance, e.g. building form, fabric, controls, thermal, visual and acoustic comfort. They are stochastic because some influences are constantly changing in ways that the tool user cannot be deterministic about, e.g. weather inferences and occupant behaviour.

In order to assess commercial codes the following question must be asked: what are the state of the art deficiencies when it comes to simulating buildings?

Method of study

This thesis covers two main aspects:

1.) Develop targets for building simulation now and in the future.
2.) Scrutinize the adequacy of tools that are commercially available against the requirements of practitioners.

In order to help define the requirements of practitioners both now and in the future, a series of structured interviews took place with industry professionals and a detailed account of this can be found in Appendix A. The main outcome of these interviews highlighted that whilst commercial codes are good in some regards, there is a need for software development, specifically in relation to cost, communities and comfort parameters.

The appraisal of the fit-for-purposeness of commercial tools must be compared with what the 'perfect' simulation tool can achieve, e.g. accurate, easy-to-use, integrative and fully dynamic. The study method was to apply tools to example problems and assess their ability to address the temporal and spatially varying performance conditions. Each program was scrutinized and an evaluation carried out as to how the tools align themselves to real performance emulation. It was quite obvious from the outset that these programs fail to meet this target for perfect simulation. If there was a compromise on that target then perhaps the tools might be able to achieve this by some level of arbitrary abstraction, however this scrutinization is benchmarked against a very high level of the explicit representation of reality.

Three methods were used to evaluate the fit-for-purposeness of the commercial tools as follows:

1.) A review of user manual instructions.
2.) A review of the online user forums populated by the wider modelling community.
3.) Construction of a hypothetical problem to explore the functionality of the program.

Hypothetical community

In order to enable the project method, a hypothetical community was created that encompasses some of the requirements a typical practitioner may want to explore for building performance. This community consists of both new-build and existing housing developments. The community is then subjected to energy efficiency upgrades, renewable systems deployments, and various other forms of simulation scenarios. Each scenario will be later explained in detail and this is then simulated to appraise how the commercial programs perform. Then the evaluation will examine the results that practitioners may wish to produce and the performance criteria necessary to convey real building performance. From such evaluations this thesis will provide a partial requirement specification for what needs to be done in future to bring commercial codes up to the appropriate standards.

Scoring

An evaluation matrix has been developed in order to assess how well commercial codes can simulate the "real world" with regard to the varying domains of integrated views of performance. In order to undertake and appraise this assessment, a range of commercial codes were scrutinized against the following five point scoring system:

1.) The software cannot handle this domain at all.
2.) The software cannot handle the domain very well.
3.) There are some features within the tool that are okay and perhaps there are ways around the software, to further analyse this issue to some degree.
4.) The software is pretty good in simulating this domain.
5.) The software is perfect in this regard.

Caveats

In order to investigate commercial codes, there are a number of caveats which concern the validity of the assessment results. These caveats are listed below.

1.) While it may be accepted that specialist research codes within the building simulation modelling community will attempt to push the boundaries of simulation, this thesis is only concerned with the evaluation of commercial codes that practitioners use across the industry.
2.) It may be expected that many of the views of integrated performance can, to some level of abstraction, be modelled. This may involve the use of third party tools to obtain source data, or it may involve a simple abstraction, e.g. imposing measured moisture source data to represent a green wall/roof. All of these codes, at some level, may be able to produce seemingly appropriate results but from a convoluted approach that is not physically based. This puts the user at risk as they not only need to be an expert in the software modelling side, but also in the technology of that particular topic. Where this is the case, it is considered that the program cannot handle the issue.

Metrics

The metric that is used in this appraisal is explicit representation and this can be broken down into three main parts and is the basis on which each domain is appraised.

1.) When the manual is scrutinized is it clear that there is a specific section on how to carry out the particular design problem in query?
2.) If it is not clear in the manual is there anything in theory that would allow the practitioner to model this particular area, e.g. third party tools?
3.) The user manuals and any arbitrary extraction for representing this domain is shown to be not possible and therefore the codes simply cannot handle this.

For this thesis, not all of the claims and areas of building performance could be tested. For example, building costs could not be considered. However, in order to cover an appropriate range of topics, the elements of building performance were split into seven categories as shown in Figure 16 and each scenario was tested within each category.

2. Practitioners' requirements

Within building design there are many considerations that a practitioner must assess and coupled with these design considerations are many different environmental effects that can take place. For this reason it is important to ensure that simulation covers a multitude of different domains and does not just focus on one particular area. Table 1 below, illustrates some of the varying environmental effects that can accrue from making one simple design decision. In this instance, the user may, for example, decide to include for smaller sealed windows to reduce heat losses in the winter, solar gains in the summer and noise intrusion from the outside. The practitioner must also take into account however, the fact that the air flow within a space is also reduced as well as the natural daylight.

Table 1 Interactions of environmental decisions (McMullan, 2007)

Design option	Possible environmental effects			
	Heating	**Ventilation**	**Lighting**	**Sound**
Sheltered site	Less heat loss and gain	-	Less daylight	Less noise intrusion
Deep building shade	Less heat loss and gain	Reduced natural ventilation	Less daylight	-
Narrow building plan	More heat loss and gain	More natural ventilation	More daylight intrusion	More noise
Heavy building materials	Slower heating and cooling	-	-	Better sound insulation
Increased window area	More heat loss and gain	-	More daylight	More noise intrusion
Smaller sealed windows	Less heat loss and gain	Reduced natural ventilation	Less daylight	Less noise intrusion

It is therefore crucial for practitioners to develop an integrated view of building performance, not just focussing on one aspect. Currently, there is no recommended method of carrying out integrated performance assessments and so, for the purposes of this thesis, the following domains have been defined for building simulation. It is worth stating that the views and domains that have been established are based on structured interviews with industry professionals as well as the authors understanding, lecture based material, literature reviews and discussions held with leading researchers in the field. This list whilst covering most aspects of building performance is in no way exhaustive of all the domains but aims to address the main spread of issues that practitioners require both now and for the future.

All building modelling can be seen in two different areas, the first is the need to specify the physical artefact and the second is to subject that to performance assessments (simulation based).

2.1. Problem specification – Physical domain

In order to specify the problem in question the practitioner must understand and model the things that can be observed in reality and the diagram below, in Figure 5, gives an overall representation of the types of systems that practitioners can typically come across;

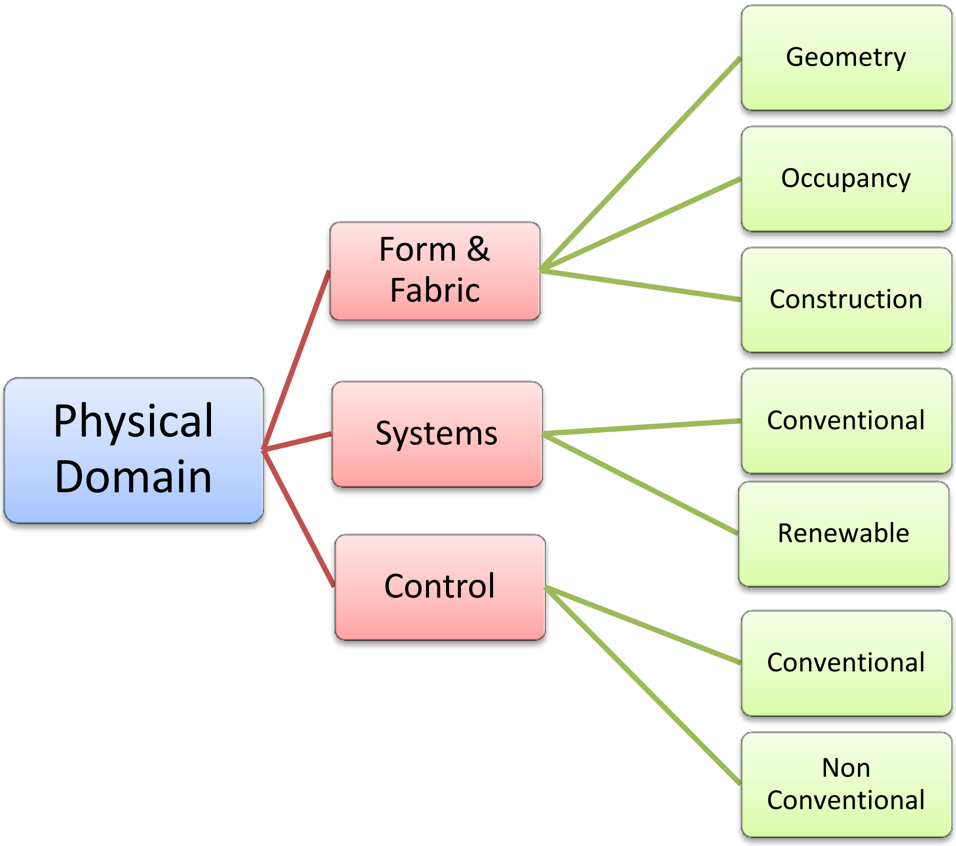

Figure 5 Physical system decomposition chart

The physical domain comprises the form and fabric of a building, the systems that will supply the cooling, heating and electricity and the placement and configuration of control system components. The specification of the physical artefacts that need to come together is a challenging aspect due to the complexity of buildings.

Form and fabric

All elements of the building must be represented in a tangible way for simulation purposes. This includes the physical building which must represent the environment in which people work or inhabit. Typically, a practitioner is required to specify complex geometries with superimposed constructions of interpenetrating materials, which will include three dimensional effects. Additionally, the practitioner is required to add in complex detailing around window frames and occupancy patterns that are constantly changing. Once this has been achieved the user will wish to define room contents, which will be placed in certain ways and will add thermal capacity or act as shading obstructions. The site must also have the correct orientation as this will affect the way in which the sun interacts with the building. So this is the target for practitioners to represent the physical artefact and this is complex in nature

This viewpoint is supported from the structured interviews. In Appendix A, Interviewee 1 mentioned that simulation should be used to understand building elements such as "glazing, orientation of the building, different roof types" and interviewee 2 mentioned the fact that location of furniture is also an important factor when considering thermal comfort. So it can be seen that establishing the correct building form and fabric is an important aspect for practitioners in order to enhance the performance appraisal process.

Supply systems

Once the physical representation of the building has been established, the user needs to specify the systems that are within the building and these can be broken down into conventional and renewable systems, examples of which are shown in the diagrams below.

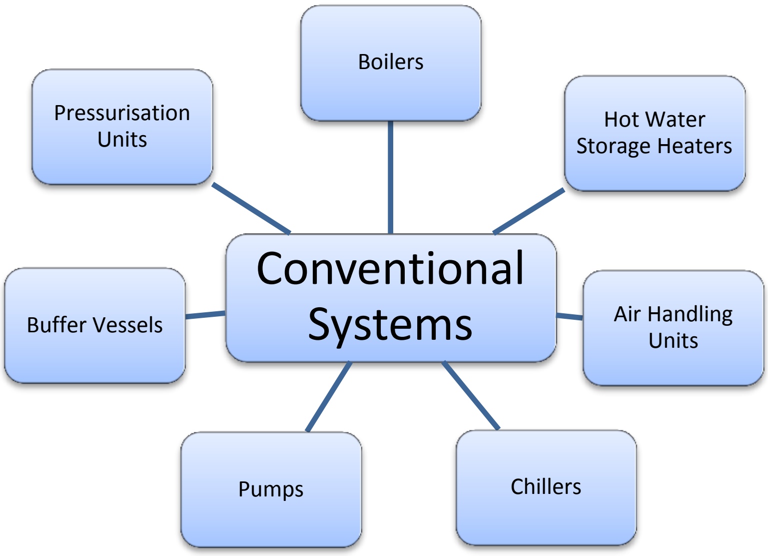

Figure 6 Conventional system examples

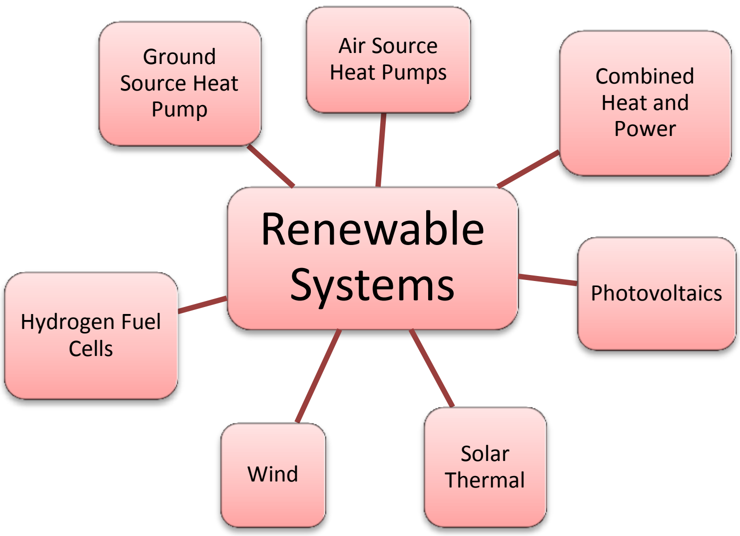

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Figure 7 Renewable system examples

Conventional systems, such as the ones depicted in Figure 6, include the more traditional HVAC systems such as boilers, hot water storage heaters, pumps, chillers and air handling units to mention a few. The renewable systems, such as those shown in Figure 7, incorporate the types of systems that are becoming increasingly important for building performance and these include air source heat pumps, ground source heat pumps, solar thermal systems, photovoltaics, wind turbines, and fuel cells.

As part of a simulation exercise, the user must be able to specify the location of where plant is situated, how it is arranged, the geometry and constructional details of the components, and the distribution system configuration, all of which will affect how the systems operate within the building. This is a complex issue for a practitioner to simulate accurately. Indeed from the results of the structured interviews, it was noted by both interviewees that the representation of renewable energy systems is important and could be better represented, as well as the importance for building simulation to take on board the representation of building energy systems and ensure that they are not oversized. This can be achieved by more accurate representation of the building energy systems under consideration.

Control systems

Once the systems have been established the controls can be prescribed. Control systems can be split into two main categories - conventional and non-conventional. Conventional control includes the ability of a system to carry out a control action in a way that represents the user/building requirements and that includes, but is not limited to, night temperature setback, thermostatic, cascade, optimum start/stop, load shedding, duty cycling, weather compensation and many other different types of control systems as depicted in Figure 8.

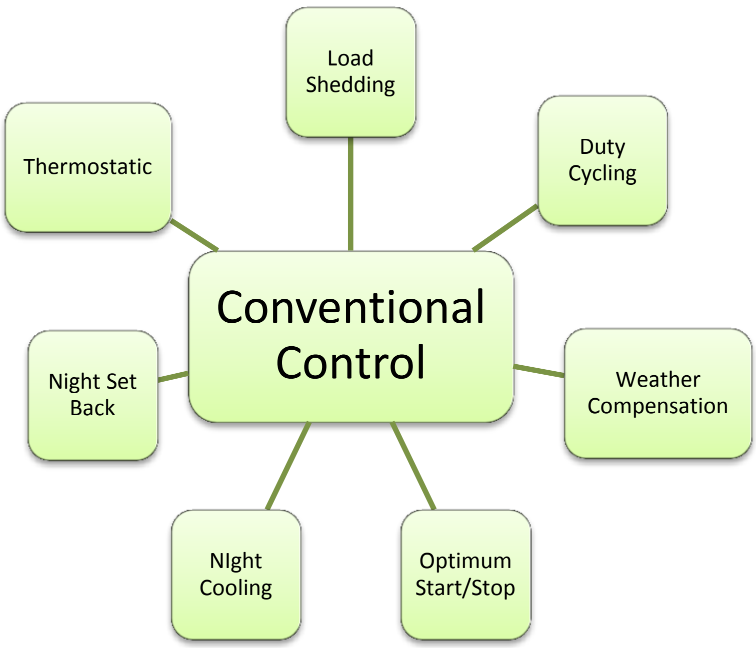

Figure 8 Conventional control examples

Non-conventional control tends to include the ability to manage systems with heuristics (the ability to learn), or model predictive control which utilises the simulation programs to execute actuators within the building. Figure 9 illustrates some examples of these types of systems.

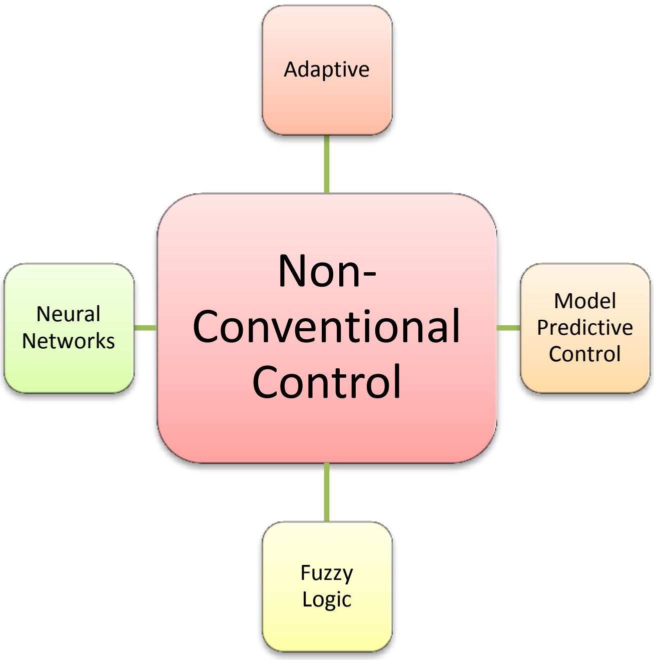

Figure 9 Non-Conventional control examples

In order for practitioners to accurately represent control systems within buildings, there are a number of issues that should be taken into account and these issues are challenging due to the complexity and nature of the problem. The user must be able to specify the location of sensors and what the control systems comprise of, e.g. for demand controlled ventilation systems, actuators must be positioned in the rooms to engage the grilles in an open or closed position based on occupancy, and pressure sensors must be situated within the main supply branch ductwork to detect differences in pressures, which will then ramp the supply fan up or down accordingly. Furthermore, there is the electrical wiring associated with controls that needs to be modelled as part of the electricity power flow network.

From the structured interviews, whilst interviewee 2 mentioned the fact that sometimes the user does not want to specify the location of ductwork or sensors, it would be a useful feature if programs could go into this level of detail if the practitioner required more accurate results from simulation. In the case of this thesis, the target of reality is to have explicit representation, so it is important to look into the systems at this level of detail.

It is clear therefore that systems need to be addressed in terms of the physical building, the systems and the control.

2.2. Problem simulation – Performance domain

Now that these parameters have been addressed, the user is required to understand more about the nature of performance and it is important therefore to adopt a performance assessment method. According to (Clarke, 2001) there are five recommended stages associated with overcoming challenges within building simulation, one of which is the performance assessment method (PAM). In order to achieve a successful application of simulation in practice, the eleven-step PAM has been developed and step 5 calls on the establishment of integrative views of performance.

Within this category there is a match complexity because simulation is a temporally and spatially varying problem and there are a lot of areas that a practitioner might be potentially interested in, especially with regard to health, comfort, glare, energy consumption and so on. This category is made even more complex due to the virtual domain of building simulation, which is a mathematical domain and requires the user to define, for instance, a mesh grid for a CFD calculation to obtain health and comfort criteria parameters. This domain however has been ignored in this particular thesis as it is assumed that future simulation will be able to automatically carry out these steps without needing the practitioner to define them.

Therefore the following parameters have been established to comprise an integrative view of performance.

Human comfort& wellbeing

In this case, commercial codes must establish all of the things that a practitioner may want to draw out of simulation in terms of its performance and this includes human comfort, which encompasses factors such as visual comfort, acoustic comfort, thermal comfort and health. Details of the factors affecting these areas are shown in Figure 10.

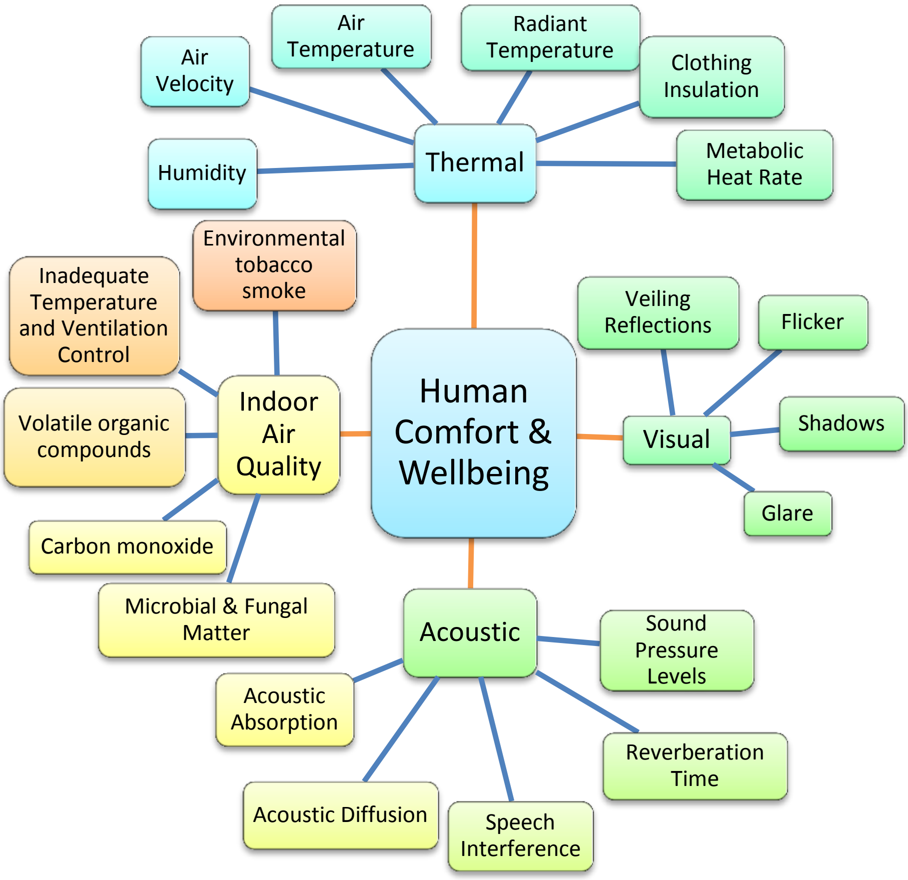

Figure 10 Taxonomy of factors affecting human comfort

In order to assess human comfort the practitioner must familiarise themselves with the criteria used to assess the various comfort parameters, details of this are shown in Figure 11. For instance, the criteria developed by Fanger (Fanger, 1972) is often used to measure thermal comfort using the PMV/PPD method (ASHRAE, 2004), or for the visual comfort criteria the Guth index is used (Luckiesh, et al., 1949). It is worth noting that in some cases the criteria is subjective (based on laboratory experiments and surveys) and therefore there is a need within industry to derive better, more dynamic methods to assess comfort. This is discussed later in the thesis.

From the structured interviews in Appendix A, human comfort and indoor air quality is mentioned as being an important performance aspect to derive from building simulation. Figure 11 gives a representation of performance criteria currently cited within industry guidance for the human comfort and wellbeing domain.

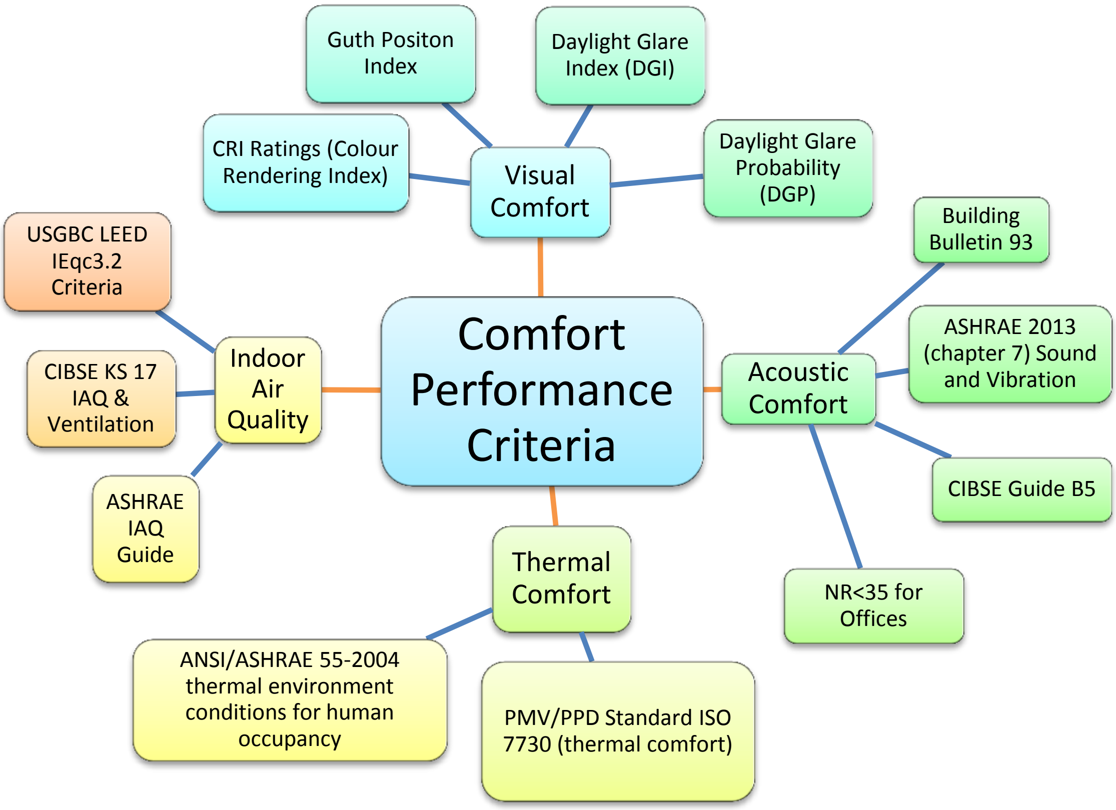

Figure 11 Performance criteria for human comfort

Building costs

The practitioner must also understand the costs associated with the building, which would incorporate running, maintenance, demolition, and lifecycle costs. In order to assess cost performance the practitioner is able to compare predicted cost performance to benchmarks and tariffs that have been historically monitored for various building types, sizes and energy use, such as CBECS (US Energy Information Administration, 2006) and CIBSE Benchmarks (CIBSE, 2008). Details of the factors affecting costs and methods for predicting them are shown in Figures 12 & 13.

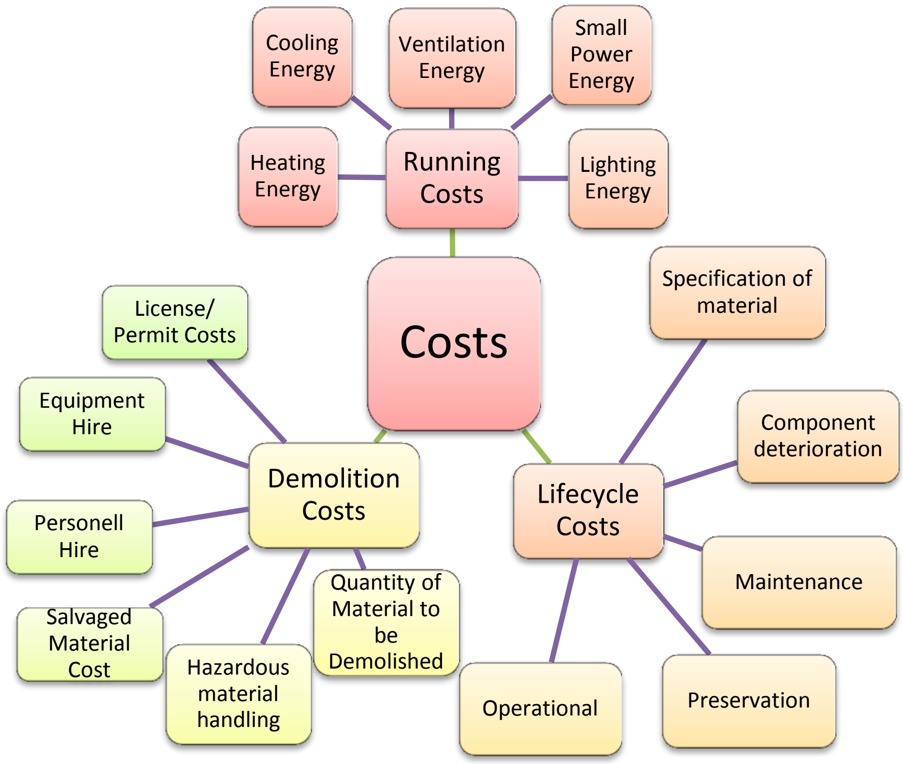

Figure 12 Factors affecting building costs

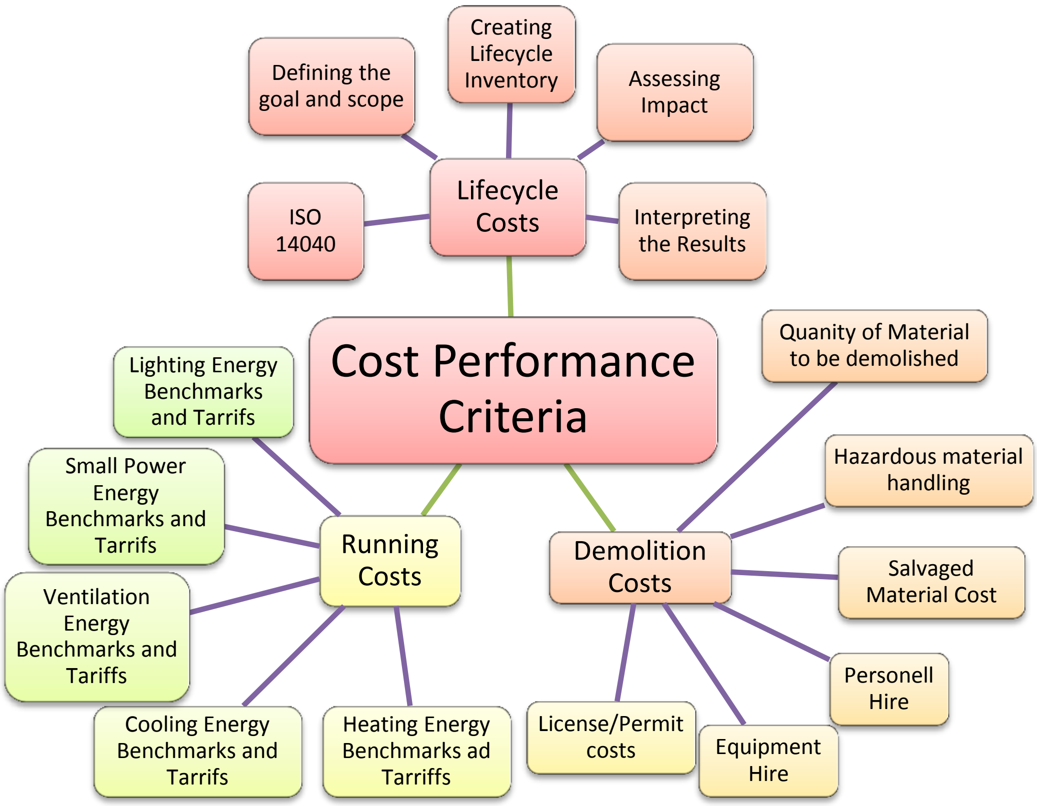

Figure 13 Performance criteria for building costs

From the structured interviews detailed in Appendix A both industrial professionals have agreed that building simulation should be able to appraise design scenarios not just in terms of capital cost, but also on a payback basis. For instance, with the use of triple glazing, although the capital cost may be high, it would be useful to see the lifecycle costs in terms of energy and cost reduction over the lifetime of the building to support design considerations at an early stage in the project. This further enhances the need for practitioners to understand more about the costs associated with buildings.

Sustainable communities

As part of a future sustainable community there are also various impacts and areas that a practitioner may wish to address, including the impacts associated with environmental emissions as well as urban heat island effects. Furthermore, the practitioner must understand the ability to incorporate smart scheduling and demand side management for renewable strategies within the community. An exemplar list of these topics is given below along with the relevant performance criteria in Figures 14 and 15.

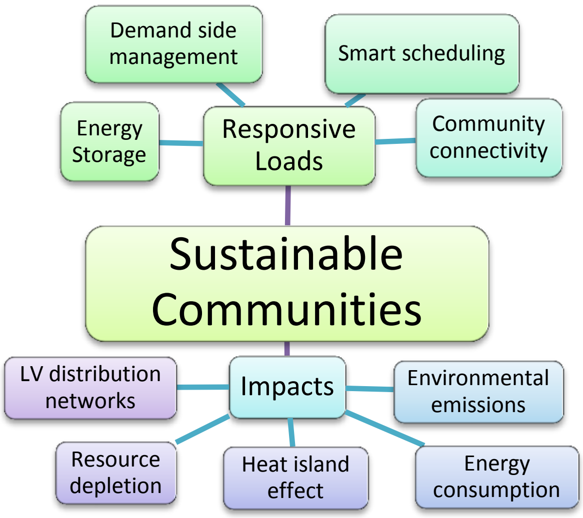

Figure 14 Factors affecting sustainable communities

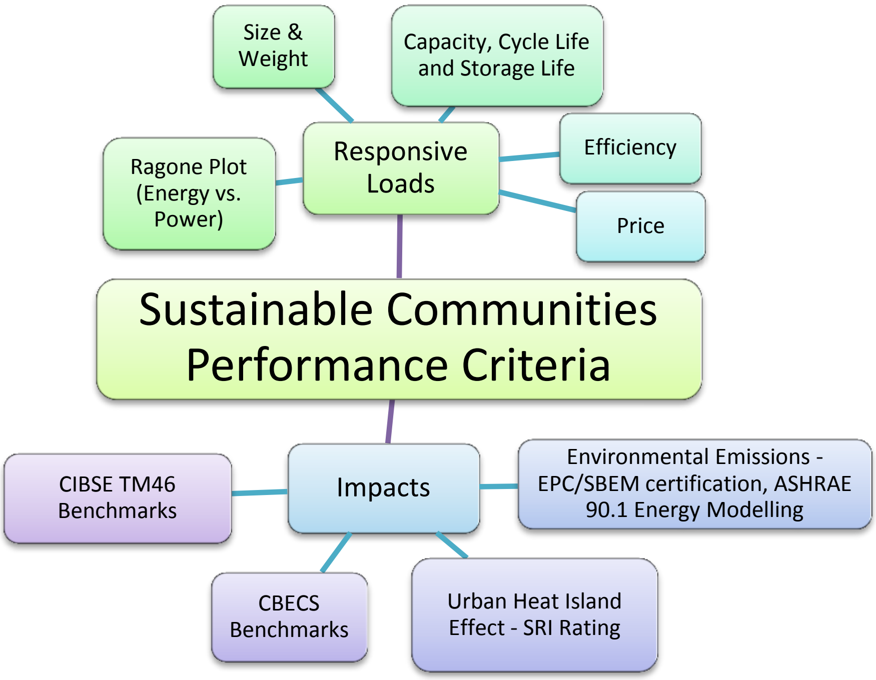

Figure 15 Performance criteria for sustainable communities

From reviewing the structured interviews of practitioners in Appendix A, it was generally agreed that this will be a more upcoming consideration in the future through the development of future smart cities and it would be interesting to consider performance at the larger scale and not just on an individual building basis.

Overall performance assessment

From reviewing the relevant requirements of practitioners, an overall performance assessment method has been established based on human comfort, cost and sustainable communities, which are summarised in Appendix C, as well as the criteria associated with these domains for practitioners to measure up against as detailed in Appendix D.

3. Current functionality & future requirements

This chapter appraises the capabilities of commercial systems against the requirements of practitioners as defined in chapter 2. As part of the evaluation of commercial tools there were some areas of the performance domains that are simply not covered by commercial codes and these are listed below:

1) Acoustic comfort;
2) Smart grid scheduling;
3) Community connectivity;
4) Supply/demand matching.

Due to the sheer magnitude of the elements involved in building performance and systems, as part of this investigation, not all of the issues could be addressed. However, in order to address a range of topics, the following diagram in Figure 16 gives a decomposition of building performance into seven categories for the scenario simulation assessment purposes. From these categories, a few example case studies have been selected to demonstrate the issues associated with each domain. It is worth noting that building costs, although commercial vendors make claims to address this category, was not assessed as part of this thesis.

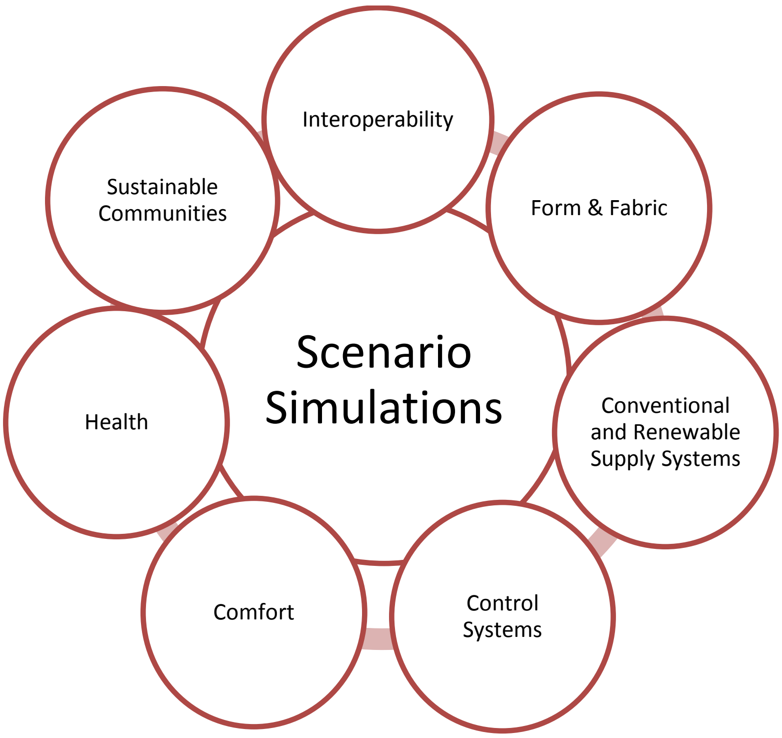

Figure 16 Scenario simulation assessment categories

3.1. Form & fabric

All buildings involve geometrical and constructional complexity of interpenetrating materials. The future of explicit simulation must be able to address conduction in the form of three dimensions and model the effects of complex issues such as: thermal bridging, mould growth, and green roofs. Typically, commercial programs at the present time are not able to address these issues fully. In some cases, there exists the ability to model these systems in a simplified, uni-directional manner but there is a requirement for commercial codes to evolve, to allow full functionality and the capability of modelling these systems explicitly, e.g. the effects of rain penetration for green roofs and three dimensional conduction gains for interpenetrating materials forming thermal bridges, to avoid condensation and mould growth. The following scenarios consider examples associated with modelling green roofs, phase change materials and insulation upgrades.

Scenario simulation 1 – Insulation upgrade in retrofit buildings

Design intent

As part of the community-wide energy improvement measures, the developer has decided to retrofit some of the older buildings by improving the fabric of the relatively poorly insulated houses within the community. Unfortunately, for some of the houses that will receive these improvements, there is no air cavity between the block/brickwork. Therefore, retrofitting insulation in the form of a stud wall is to be added onto the inner layer of the wall construction. A modelling exercise must now be carried out to determine the nature of the insulation improvements and the effects that this will have on energy consumption and indoor air quality.

Vendor claims #2, 5, 7, 23, 33, 39

For this scenario, the vendor claims that will be tested include; the building heat balance based on interior and exterior conduction, contaminant dispersal, condensation calculations from construction, indoor air quality, indoor environmental quality and passive design components related to insulation.

Introduction to insulating homes

With government incentives like the Green Deal it is becoming increasingly popular and cost effective to employ energy improvement measures within existing homes. As part of this scheme, measures covered by the Green Deal (Deparment of Energy & Climate Change, 2014) include insulation of homes. It is estimated that the cost of doing this is relatively cheap in comparison with other technologies with reported payback periods of less than four years (Homes with Green, 2014).

Insulation principles

In order to model the effect of adding in new insulation, a fabric heat and mass transfer algorithm must be carried out. Firstly, a model must be created in order to represent the existing building as close as possible. Information on the fabric properties of the construction materials, the window/door openings, the geometry and orientation all must be inputted for model construction purposes. Once the existing building fabric properties have been obtained and the resistance values and U-values are known, the additional internal insulation can be added to the overall construction. For the purposes of this exercise, the following parameters were used for a typical brick/block wall insulated to 1985 regulations at 0.5130 W/m^{2}K, as shown in Table 2.

Table 2 Material properties of 1985 brick/block wall

Material	Thickness (mm)	Conductivity (W/m·K)	Density (kg/m³)	Specific Heat Capacity (J/(kg·K))	Vapour Resistivity (GN·s/(kg·m))
Brickwork (outer leaf)	100	0.84	1700	800	58
Mineral Fibre Slab	50	0.0350	30	1000	6
Concrete Block	100	0.510	1400	1000	120
Gypsum Plasterboard	15	0.42	1200	837	45

As part of the fabric upgrades, a 60mm polyurethane board is added to the internal surface of the material, resulting in an improved overall U-value of 0.2299 W/m^{2}K, as shown below in Table 3.

Table 3 Material properties of improved brick/block wall with additional P.E. board

Material	Thickness (mm)	Conductivity (W/m·K)	Density (kg/m³)	Specific Heat Capacity (J/(kg·K))	Vapour Resistivity (GN·s/(kg·m))
Brickwork (outer leaf)	100	0.84	1700	800	58
Mineral Fibre Slab	50	0.0350	30	1000	6
Concrete Block	100	0.510	1400	1000	120

Polyurethane Board	60	0.0250	30	1400	550
Gypsum Plasterboard	15	0.42	1200	837	45

Generally, for the purposes of this exercise, the practitioner is concerned with the thermal performance and energy consumption of the building with the improved fabric properties. However, referring to chapter 2 and relating this to the requirements of practitioners, the user is also wary of indoor air quality issues and thermal comfort as a result of this added insulation. The reason that this is an important issue to address is that in some cases, by adding insulation to the existing fabric, the risk of dampness becomes a greater concern due to cold spots and thermal bridging resulting in condensation build up and mould growth, which can affect the health of the occupant.

In order to model these thermal bridges, the practitioner must first have a model that is three dimensional, as there will be three dimensional movement of heat flux to consider. In this scenario, there will be some cases where the polyurethane insulation is at a junction with the cantilevered concrete floor, causing the movement of heat flow to increase at first floor level. For the construction elements surrounding the steel lintels above the windows, the movement of heat flow is also increased considerably as depicted in Figure 17 and 18 below.

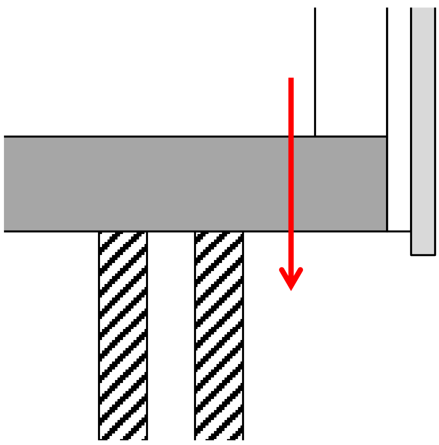

Figure 18 Cantilevered concrete floor

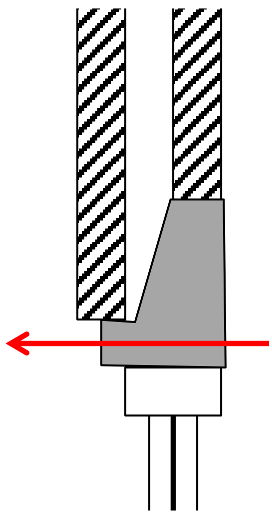

Figure 17 Boot lintel over window

Therefore, in order for practitioners to assess the impacts of this, tools need to be able to address not only the thermal performance but also the contaminant dispersal that might result from this measure of fabric "improvement".

How the programs perform

Now that the case has been established as to how this type of problem would be tackled, the critical appraisal of commercial programs can be assessed. The codes can provide, to some degree, a dynamic thermal model of assessing the heat flow through materials from a uni-directional point of view, which gives a depiction of heat flow in a one dimensional case.

From reviewing the user manuals, it is difficult to explicitly model the three-dimensional nature of heat flux flow of interpenetrating materials within any of the codes. Furthermore, there is no obvious feature within the commercial tools that allows the user to begin to model the effect of interpenetrating materials and nothing is clearly stated in the user manuals of how thermal bridges could be explicitly represented. There are however some engineering approximations that can be applied. These approximations can be attributed separately to non-repeating and repeating thermal bridges.

For repeated thermal bridges, the current recommendations given by commercial vendors on the online forums are to input adjusted U-values that manufacturers of insulation sometimes provide. This takes into account the likes of repeated bridges, such as where floors/walls are supported by multiple wooden joists. The adjusted U-value method, or the linear thermal transmittance value method, φ, in this case is adopted. The linear thermal transmittance of a thermal bridge is "the rate of heat flow per degree per metre of the bridge that is not accounted for in the U-values of the building elements around the thermal bridge" (McMullan, 2007).

In this case, the φ values for two and three dimensional heat flow calculations can be modelled more accurately, although not explicitly. Once the φ is known then the additional heat loss through thermal bridge can be calculated:

$$H_{TB} = (Lx\varphi)$$

Equation 1 Thermal bridging equation

L in this case is the length (m) of the bridge over which the φ value is applied. H_{TB} is the transmission heat transfer coefficient.

In order to obtain the total conduction heat loss through the construction element the values for H_{TB} can be added to each of the elements of the fabric and the equation is then amended to the following.

$$\sum H_{TB} + \sum U \cdot A$$

Equation 2 Total conduction heat loss

For the purposes of regulations compliance, commercial code experts suggest that in some cases the calculation of thermal bridging is carried out by simply adding in ten percent of the U-value or by inputting dummy zones such as doors or additional construction materials to simulate this kind of bridging effect (BRE, 2010)(NCM Modelling Guide).

This however is only carried out to determine CO_2 emissions of a building and not to address issues such as thermal comfort or indoor air quality. Commercial tool vendors state that this engineering simplification is applied because of the limitation in the software, due to the fact that each surface has only one temperature node, thus there is no way of generating a thermal image of junctions. These methods, including the adjusted U-value method, are crude and not realistic in terms of how the thermal bridging occurs and so developments in this area are required.

Industry guidelines refer to the combined method approach (BRE Scotland, 2006) (BS EN ISO 6946, 2007), this method involves calculating an upper and lower limit of thermal resistance in the element to obtain an averaged value. Whilst this method may lie within the limits of the thermal resistance, if the difference between upper and lower limits is fairly significant then this is an inadequate approximation of the equal weighting of the result and is therefore fundamentally flawed for thermal bridges that are non-repeating.

For non-repeating thermal bridges, and to truly simulate the three dimensional effects of thermal bridges, there are third party numerical software modelling tools that can deal with this detailed type of numerical calculation such as LBL’s Therm (Buildings Energy & Sustainability Group , 2014). However, as mentioned, commercial tools should aim to be integrative and assess all of these aspects, including thermal bridges, in one simulation package. Furthermore, the third party tools are not compatible with commercial codes within the UK and it would be very difficult to import a three-dimensional model of this nature into the existing platform.

From this analysis it can be seen that by carrying out a simple exercise such as the addition of internal insulation, there are many factors that practitioners want to assess such as indoor air quality, heat transfer, condensation dispersal analysis and mould growth. In this scenario described, it can be seen that commercial codes cannot represent, in this instance, an accurate representation of these issues due to the three dimensional nature of the problem. It is clear from this analysis that the future simulation capabilities and functionality of commercial codes should be able to adopt algorithms that can model the effects of this three-dimensional nature of heat flux flow caused by interpenetrating materials. This can either be achieved by adding this type of functionality to the commercial codes, or by ensuring that codes are able to improve in their interoperability and exchange information better between third party application tools.

Scenario simulation 2 – Green roof and phase change materials

Time adaptive materials

The future of building simulation requires practitioners to be able to assess materials of increasing technical complexity that adapt in accordance with time, for example the likes of phase change materials (PCM), building integrated photovoltaics (BIPV), thermo-chromic, photo-chromic, electro-chromic glazing, green roofs, movable insulation and many other types of materials. In the case of movable insulation e.g. motorised venetian blinds, there is technical complexity involved with how the blinds move with respect to time. For example a motorised valve must be simulated to open and close each individual slat according to shading, lux levels and overheating within a space. This is naturally very difficult to represent in building simulation. Other examples such as electro-chromics will have a transmission factor for a window however all electro-chromics consist of biangular transmission (Lee, et al., 2002). PCM's will have melting temperatures from solid to liquid but there will also be an in-between phase of the material, which will comprise of a mixture of solid and liquid elements. This will affect the transfer of latent heat within a room and so, it is physically difficult to represent these materials whose properties are constantly changing with respect to time.

It can be deduced that the majority of the codes do not have the explicit facility to model these types of time adaptive materials and in other cases, they are able to model this but in a crude way. The bulk of commercial codes however cannot define or even create these materials e.g. PCM materials, green roofs or thermo-chromic glazing are not listed within the materials library database. There are ways in which the systems can be modelled in a more simplified but abstract way by using control loops and other means to represent the behaviour of such a system but, by and large, the commercial codes need to evolve more features and capabilities in order to accurately simulate the effects of these time adaptive constructional materials. In order to test this subject, the hypothetical scenarios below, were considered for green roofs and PCM's.

Design intent

As part of a speculative new build development, the practitioner is required to simulate a new primary school building and as part of this development, the practitioner wishes to include a green roof and phase change material partitions within the building, in order to minimise carbon emissions and store energy in the form of heat.

Vendor claims #9 and #40

Referring to Appendix B vendor claims include; the ability to simulate green roofs and the ability of models to incorporate thermal storage for phase change materials (PCM).

Green roof principles

It is becoming increasingly popular within modern architecture to include green roofs within the design of sustainable buildings. Not only do green roofs provide good means of irrigation and thermal performance, specifically in terms of passive cooling, they also improve the community due to the limitations associated with the impacts of the urban heat island effect. This is due to the fact that the roofs have a relatively low solar reflectance index (SRI) value (USGBC, 2008). Therefore, it is becoming increasingly important within industry to effectively model these materials to assess the true nature of building performance.

Plants for instance, have a unique ability to protect the building from solar gains, control the indoor air quality in terms of humidity and temperature and also protect the building from the availing wind patterns (Niachou, et al., 2001). In order to effectively model these fabric types, the simulation requires input information relating to the height of plants, leaf area index (LEA), leaf reflectivity, leaf emissivity, minimum stomatic resistance, thermal conductivity of growing media and solar absorptance as well as the effect of precipitation and moisture content within the soil matter (Padovani, et al., 2003). Naturally, this type of technology is a heat and mass transfer problem and does not have a uniform geometry, so this is a particularly challenging problem to effectively simulate.

PCM principles

PCM's have the ability to store a large amount of thermal energy per unit mass compared with conventional building materials, this is due to the fact that the energy being stored is latent rather than sensible heat. It is this latent heat storage that is of particular interest for the modelling process and it is in this case that it is based on the "heat absorption or release of when a storage material undergoes a phase change from solid to liquid or liquid to gas" (Sharma, et al., 2007).

For example, when assessing the paraffin wax type PCM that is often used in building partitions, a program will need to recognise and emulate the behaviour of such a material. In this case when the temperature of the room reaches 22 degrees Celsius, due to solar gains or external temperatures, it changes state from solid to liquid and therefore all of the heat from the room is stored in the wax. Likewise, in the reverse order, if the temperature is to drop below 18 degrees Celsius, the material remains in a solid state and releases the heat back into the environment. This type of behaviour is an example of thermal storage, but the way in which the material behaves is very different to normal thermal mass problems.

How the programs perform

Green roofs

For most of the codes, the ability to model green roofs is invariably difficult, whilst most construction libraries have soil types within the materials library database, the majority do not take on board the effects of precipitation, moisture content, leaf area index and other evapotranspirative properties that are specific to the performance of green roofs. Therefore, the simulation that is carried out is not accurate or explicit in representing the true benefits of having green roofs. There is however one commercial code that offers the user further input parameters, such as precipitation data, however the data that is referred to in the user manual is only available for the US and so presumably users would be expected to obtain precipitation data in metres per hour for light/moderate and heavy rainfall associated with the particular location in the UK. It is unclear if such data is readily available to the practitioner for UK climates. The green roof model in this particular code takes on board the following parameters as shown in Table 4.

Table 4 Green roof simulation capabilities

Capability	Performance characteristics
1	Long wave and short wave radiative exchange within a plant canopy
2	Plant canopy effects on convective heat transfer
3	Evapotranspiration from the soil and plants
4	Heat conduction (and storage) in the soil layer

Programs however cannot take on board the effect of the moisture-dependant thermal properties of green roofs. Also, due to the nature of the algorithm involved, the energy and moisture balance is only considered in a one-dimensional case and draws heavily upon the algorithms developed by BATS (Dickinson, et al., 1996) and SiB (Sellars, et al., 1985). These models however, are described as being simple models and not ones that can deal with the arbitrary complex nature of green roofs. The user, in one instance of the commercial codes, can enter in other green roof aspects such as growing media depth, thermal properties, plant canopy density, plant height, stomatal conductance, and soil moisture conditions. From these input parameters the tool is able to simulate the following parameters as shown in Table 5.

Table 5 Green roof simulation output parameters

No.	Output parameters
1	Simplified moisture balance that allows precipitation, irrigation and moisture transport between two soil layers (top and root zone).
2	Soil and plant canopy energy balance based on Army Corps of Engineers' FASST vegetation models (Frankenstein & Koenig), drawing heavily from BATS (Dickinson et al) and SiB (Sellers et al).
3	Soil surface (T_g) and foliage (T_f) temperature equations are solved simultaneously each time step, inverting the CTF to extract heat flux information for the energy balance equation.

Whilst this particular code may give a good estimation of the energy reduction measures that green roofs can be attributed to, it does not give the user explicit complete representation of how the green roof would affect the performance characteristics of the building such as passive cooling, indoor air quality and other domains. Furthermore, it was only one of the commercial tools that provided evapotranspiration features for analysis, and therefore the others, whilst claiming that they could simulate green roofs, could not even begin to represent this type of technology.

PCM's

Phase change materials are also complex in their behaviour and so commercial codes must have the ability to clearly capture this. Out of all of the tools reviewed, only one of these provided a free downloadable plugin that assessed the thermal performance of phase change materials developed by a commercial supplier of PCM's.

For the codes that do not have the explicit function to model phase change material, there is a way to 'trick the software' into representing the behaviour of such a technology. In this case, from reviewing the user forums, PCM's can be modelled by inserting a cavity adjacent to the material under consideration. A control set-point is then determined, in the case of the paraffin wax insulating material, the melting set point would be 22 degrees Celsius. When the temperature rises above the melting point of the wax, the energy transfer switches into the conditioned space. This energy transfer will include all of the latent heat that can be accounted for the phase change material in question. Once this has reached its limit, the conditioning is turned off and this will allow the materials temperature to rise in the normal manner that it would do. The same process is reversed in the event of solidification.

This solution requires the user to setup a control loop that involves considerable manual intervention to ensure that the system will operate in the correct manner, this also becomes quite complex for an annual simulation (better for design day simulations) (Kendrick, et al., 2007). The process is therefore crude and long winded and assumes that the rate of heat release of a material behaves in a constant, steady state condition. The other commercial code that does provide a plug-in for phase change materials, allows the user to assess a building with or without phase change materials. This software has been validated against real buildings and therefore provides the user with a good understanding of how these phase change materials affect thermal performance. It would be interesting to test and validate this software in further depth to see how the code reacts to instances where partial solidification of a PCM occurs and how the distribution of latent heat is stored and emitted in these cases.

From the results it can be deduced that, whilst commercial codes are found to be good for modelling cases that have uni-directional conduction heat and mass transfer flow, the accuracy of these results is somewhat lacking when it comes to problems that are three dimensional in nature e.g. thermal bridging. Likewise, for materials that are time adaptive such as green roofs and PCM's, most of the codes cannot simulate the evapotranspiration effects as well as phase change behaviours that are more complex than steady state materials. Whilst these types of materials are not readily used in building design at this present stage, it is envisaged that these time adaptive materials will become more and more popular as the drive towards a zero carbon future progresses. It is therefore imperative that all commercial codes ensure that the functionality of simulation is developed to model these types of issues explicitly, in a three-dimensional way, including for evapotranspiration properties of materials, and the dynamic, non-linear nature of phase change materials.

3.2. Conventional & renewable supply systems

The systems section can be divided into two categories;

1) Conventional
2) Renewable

Their deficiency, in one regard, is due to the fact that they cannot take on board the dynamic, transient nature of building systems and tend to require the user to input parameters such as pump power, distribution losses and part load efficiency curves.

All commercial codes persist in requiring the user to give what's effectively an output from the simulation as an input, in the form of a part load efficiency curve. However, if the model was truly simulating the boilers performance, then the load at any given time step could be ascertained by the practitioner and not required as an input to simulation. This is the same thing as a practitioner requiring to input the air change rate into a building, however if the building is being modelled correctly then the simulation should predict the air change rate at any given time and not vice versa. The following simulation scenarios have been established to test these claims and examine them in further detail.

Scenario simulation 3 – Boiler upgrades in retrofit buildings

Design intent

Due to the installation of new gas supply network within the community, the practitioner has been given the task of upgrading the hydronic heating systems from conventional oil fired boiler systems to a more efficient gas fired boiler system. The practitioner is required to show the energy savings and improved boiler performance that could be attributed to these energy improvement measures.

Vendor claims #40, #48, #51

The ability to assess active systems including heating systems and to assess available plant capacities for heating and cooling loads.

Boiler system performance principles

To effectively model a boiler heating system there are various input parameters that will dictate the way a boiler operates. These parameters according to (Kenna, et al., 2009) include for;

1.) The boiler and distribution system standing losses;
2.) Thermal mass of the fluid in the distribution system;
3.) Purge losses during the cyclic operation and during burner ignition;
4.) Minimum/maximum output capacity at which the burner can continuously operate;
5.) Burner combustion efficiency;
6.) A "cut out" ambient temperature of which the boiler will not operate (lockout control);
7.) Design operating temperature of water in the system.

All of these factors will describe the way in which a boiler behaves and most of these parameters can be obtained from the manufacturer itself. Furthermore, in order to determine how the boiler operates, the demand associated with the heating system is required. For this the practitioner must have a dynamic building heating load profile that represents the systems within it. Therefore the demand of the heating requirements within a building and the operating characteristics of the boiler must be combined to assess the way in which a heating system behaves within simulation.

How the programs perform

Within commercial codes, and from reviewing the user manuals, there is the ability to model the boiler itself and as part of this process the practitioner can enter the following input parameters:

1) Boiler system e.g. condensing, natural draft, electric etc.;
2) Part load efficiency curves;
3) Boiler output;
4) Distribution heat losses;
5) Fuel type;

6) Pump power;
7) Pump usage pattern and system efficiency.

These parameters are then used to model the boiler performance against the building heat load demand. From the previous section it is clear that there are many aspects of boiler performance that must be assessed, however the codes simply ask for input parameters from the user such as the part load efficiency curve. Therefore, it can be deduced that the boiler simulation is not taking on board the instances when the system has to shut down due to boiler lockdown, or how the system reacts to the thermal inertia of water that must be heated, or the purge losses associated with burner ignition. All of these factors, and more, cannot be modelled and therefore the simulation is not taking on board the dynamic nature of the boilers operational behaviour, it is using a simplification in a part load efficiency curve that is not reflective of "real" explicit representation of boiler performance.

Furthermore, the user must establish the distribution losses associated with the system in question e.g. for a hydronic radiator system the user must calculate the heat loss through the distribution system so that the boiler can add this loss to the overall load. The pump usage patterns must be determined for each part load efficiency point (up to ten can be defined), this requires the user to understand how the pump will perform and enter this as a function of percentage. The software will then use linear interpolation between the points to establish the performance between part load efficiency nodes. This is particularly difficult to determine as pump behaviour is quite complex in operation.

It can be seen that in order to address the improvement of boiler upgrades in buildings, commercial codes are far away from providing users with accurate, dynamic performance data for analysing energy improvement and performance characteristics of conventional boiler distribution systems. As part of the future capabilities of commercial codes, the tools should look to incorporate ways in which to model the operational characteristics of boiler systems, taking on board aspects such as thermal mass within the distribution system, purge losses, lockout control etc. and not require the user to simply enter a part load efficiency curve.

Scenario simulation 4 – Natural ventilation strategies

Design intent

As part of the new school development, the practitioner is required to establish a single-sided natural ventilation strategy in order to meet the overheating criteria, as stipulated by industry guidance and building bulletins (DFES, 2006).

Vendor claims #20, #39

Passive design components, including the ability to simulate natural ventilation within buildings and thermal simulation of naturally ventilated buildings.

Natural ventilation modelling principles

In order to assess natural ventilation within a room, there are many parameters that must be addressed in order to effectively model this type of scenario. Firstly, the building must be modelled with the right amount of openings associated with it, in this case, it relates to window openings, typical details of which can be seen in Figure 19 below.

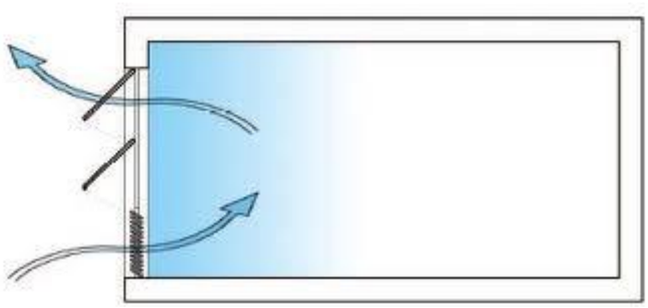

Figure 19 Single sided natural ventilation strategy (Scottish Executive, 2007)

The nature of the window opening must first be represented, in this case the window is top hung, and opens by a 45 degree angle, the window will open manually and does not have any controls associated with it. Once the systems have been set the calculations can be carried out. The first thing to address is the stochastic nature of wind pressure in and around the building, which affects the flow of air into a room. This is complex in the fact that it is dependent on the wind speed, direction and building geometry. For practical purposes, the wind pressures are usually calculated using the wind pressure coefficient. In this case, the coefficients relate to wind pressure on a building surface, wind speed and direction and can be defined by the following equation;

$$P = C_P \rho v^2 / 2$$

Equation 3 Wind pressure/coefficient calculation

Where

P - wind speed
C_P - wind pressure coefficient
ρ - air density
v - reference wind speed

The second issue is that of buoyancy, caused by the pressure differences within a space particularly between two different heighted openings, causing pressure differences between the high and low level areas of a room. The distribution of draft within a space is another area that requires accurate representation as this will affect air flow distribution within a building particularly through cracks in windows and other openings.

How the programs perform

Most of the commercial codes have specific modules that allow the user to physically represent window openings by specifying the type e.g. in this case top hung, as well as the percentage of opening and maximum angle of opening. Furthermore, the user can specify the crack flow coefficient measured in $l/(s \cdot m \cdot Pa^{0.6})$ and the user can specify either an on/off, continuously opening, or specific user-made profile. The difficulty with modelling this type of system relates to how cracks can be represented, the user must estimate a crack flow coefficient in order to assess the draft that might result from a poorly installed window, however this is based on estimation only, actually modelling the air flow (draft distribution) as a result of cracks is very difficult to estimate.

Putting these input parameters aside, the user is also restricted in specifying occupant behaviour. For instance, if an occupant decided to leave a window open at night, the model does not take on board the fact that the user will be asleep for the duration of that period preventing him from closing the window until the morning when the temperature has dropped way below the set point for when the window closes again. Furthermore it is also difficult to model the opening profile of a window that is manually operable, the simulation allows for constant, daily, weekly, annual profiles but in reality this is not likely to reflect the way in which the building will operate due to the intermittency of occupancy and the unexpected nature of occupants behaviour, with some occupants' preferring warmer climates and others not.

The simulation codes are able to produce results that give annual output data as well as hourly snapshots of the distribution of temperature, pressure and velocity of the air within a room. However, the climatic data that is used is based on hourly information, and for the purposes of a single sided natural ventilation strategy, the user is not able to input weather data that would include for a more accurate distribution of climate data, e.g. minute by minute. This lack of functionality can affect the accuracy of the results in question, particularly with single sided ventilation strategies that can vary quite drastically within an hourly period.

In summary, whilst the codes can perform quite well in modelling the attributes of natural ventilation strategies e.g. window openings, crack flow coefficients and opening profiles, there are still some areas that require development. The future of commercial codes should take on board issues such as occupant behaviour and opening profiles and model them in a more effective way, by the creation of dynamic occupant behaviour models that could be inputted into the system. Further complexities with cracks and leakiness within a building could also be modelled more effectively with less emphasis on inputting coefficient based parameters, and also increasing the time steps for weather data to ensure the distribution of air is modelled more accurately and not on an hour by hour basis.

Scenario simulation 5 – Use of air source heat pumps

Design intent

As part of a new school development within the community, in order to meet the renewables obligation, the practitioner is required to design the instalment of an air source heat pump system to serve the heating demand of the new build school.

Vendor claim #11

The ability to simulate renewable energy systems including air source heat pumps.

Air source heat pump principles

Air source heat pumps are increasingly becoming a more popular choice of heating/cooling systems within buildings due to their relatively high coefficient of performance (COP) and can achieve up to 3 or 4 units of energy out from just one unit of energy in. Despite air source heat pumps relying on electricity sources to run them, they are still categorised as being a renewable source of energy, due to their relatively high COP’s. In order to effectively model these systems, there are a few principles that need to be understood.

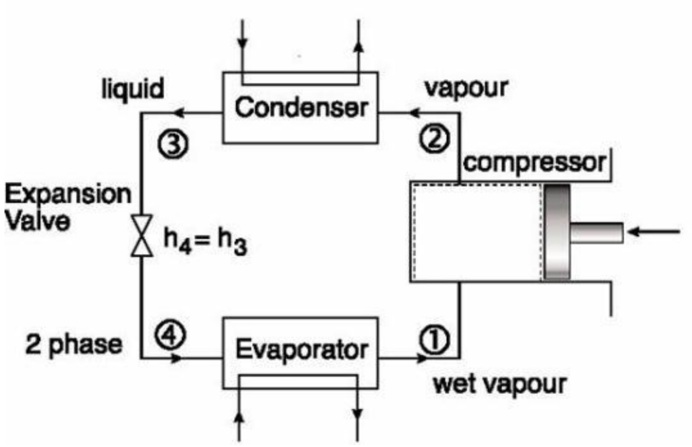

Figure 20 Air source heat pump refrigeration cycle (Kazuli, 2002)

The way in which a heat pump operates is typically through the vapour compression cycle, whereby a refrigerant enters the evaporator coil and absorbs the heat from a low grade temperature source – in this instance, the air. As the refrigerant goes through the compression stages, the temperature of the refrigerant increases and then passes through the condenser stage whilst releasing the heat, which is used to heat the water that serves the heating coils within the building, the refrigerant then expands and repeats this process cycle. A typical refrigeration cycle that is common to air source heat pumps is illustrated in Figure 20. In order to effectively model this process, the user would need to determine the temperature of the hot and cold surfaces that the heat pump operates between at any given time. The main equation associated with the coefficient of performance can be expressed in the following equation;

$$COP_H = \frac{HeatEnergy\ Output}{Pump\ Energy\ Input} = \frac{T_1}{T_1 - T_2}$$

Equation 4 Coefficient of performance

Where:
T_1 – absolute temperature of heat output (K)
T_2 – absolute temperature of heat source (K)

There are however certain issues that affect the COP such as:

1) Frictional losses from evaporator to condenser;
2) Heat losses to surroundings;
3) Flashing in the expansion valves;
4) Superheating prior to compressor stage;
5) Sub-cooling prior to evaporator stage;

6) Intercooling between stages;
7) Defrost cycles.

All of these issues surrounding heat pump performance affect, to some degree, the operation and resultant output performance of heat pumps.

How the programs perform

Within commercial codes, there is the facility to model heat pumps by allowing the user to input a part load COP profile. In this instance, COP values can be entered for up to ten source temperatures, the tool then linearly interpolates between each value to achieve a spread of performance over the varying temperatures. This allows the tool to assess performance of the heat pump at any given time step based on outside air temperatures. The problem with this type of system is that the part load curves are not always known and it is, in some cases, the manufacturer that is only able to provide a seasonal COP, which is an averaged performance value over a typical year.

A better approach to modelling air source heat pumps, and indeed what the simulation codes must strive to achieve in the future, would be for the programme to calculate what the COP of the air source heat pump would be at any given time. In this case the model would incorporate and simulate all of the stages of the refrigeration cycle from evaporation to condenser side and the practitioner would be able to enter the type of refrigerant and the type of air source heat pump. The tool could then model the effects of temperature, frictional losses, heat losses, flashing, defrost cycles, on-off control methods and all other things associated with heat pump operation to determine the performance of the heat pump for the user, based on internal and external temperatures.

Scenario simulation 6 – Use of solar thermal heating systems

Design intent

The practitioner is required to consider a solar thermal hot water system due to the large demand of hot water in the changing rooms of the new school development. The roof has an available 6 m^2 for the installation of evacuated tube plate collectors with a solar storage tank and automatic drain-back feature within the collectors.

Vendor claim #11

Commercial codes have the ability to appraise low carbon technologies including the incorporation of solar thermal heating systems.

Solar thermal heating principles

Solar thermal heating systems comprise of various components consisting of the solar thermal panels in either an evacuated tube or flat panel format right down to the solar storage tank and coils used for heating the hot water and feeding the distribution system, an image illustrating the various components in a typical system is depicted in Figure 21.

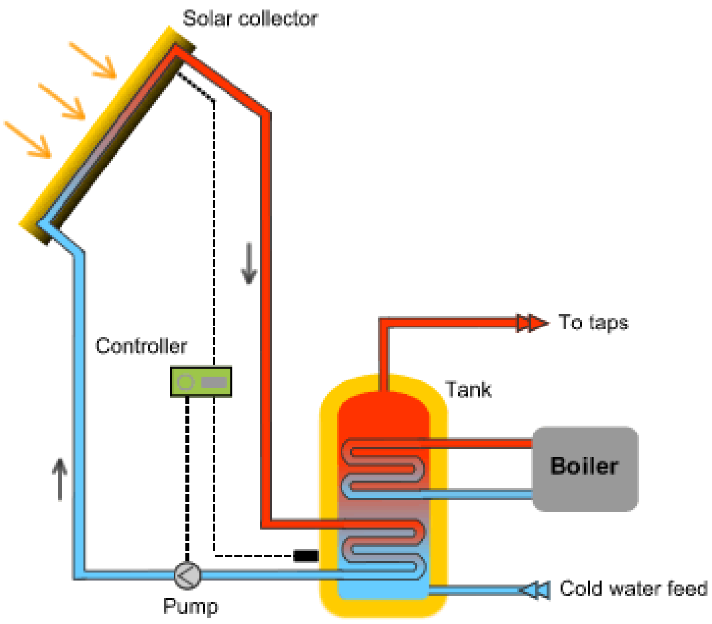

Figure 21 Solar thermal hot water system (UK Solar Energy , 2013)

The first component that needs to be effectively modelled is the evacuated tubes within the solar panels, these are essentially a row of glass tubes that link up to a header pipe where all of the air is sucked out of the system to minimise heat losses through the pipes. A solar fluid is then connected to a copper or aluminium fin within the glass tubes, which transfers heat to the solar fluid. This solar fluid is then pumped through to a solar storage hot water tank and a solar coil within the tank is then used to heat up the water to the desired temperature, in most cases a back-up system is also provided via a gas fired or electric heating element to ensure the temperature is always met regardless of external climate conditions.

The characteristics of the evacuated tubes and heat exchange process between the aluminium or copper fin to solar fluid must be effectively modelled. To do this the component of the sky vault must be modelled in order to determine the dynamic estimation of direct and diffuse radiation, the process of the pumping of the fluid from the solar thermal panels to the plant equipment must also be modelled, including all heat losses associated with the length of pipework run and also the heat exchange effectiveness between the solar coil within the heating tank and the hot water distribution system.

How the programs perform

Within commercial codes there is the ability to specify the type of system in question including; the aperture area of the solar panel (m^2), azimuth angle in degrees clockwise from North, the panel tilt in degrees from the horizontal, the shading factor, the first order heat loss coefficient a_1 and the second order heat loss coefficient a_2. The heat loss coefficients are based on the performance of the device in terms of a conversion efficiency at ambient conditions, η_0, all of which are claimed to be available from manufacturers' data. The following equation is used to calculate the heat output per unit panel area.

$$W = \eta_0 l - a_1(T - T_a) - a_2(T - T_a)^2$$

Equation 5 Solar thermal heat output calculation

Where
W – heat output per unit panel area
I – incident solar irradiance (after inclusion of shading degradation)
T – panel temperature
T_a- outside air temperature

The commercial codes also include an input associated with the fluid flow rate per unit area of the solar panels and the rated pump power within the system. The code also models the heat exchanger effectiveness within the system and assumes that the collector loop uses a heat exchanger in the form of an internal coil or external heat exchanger. This requires an input from the user to determine this factor, which is the ratio of the drop in temperature across the heat exchanger on the collector loop side to the maximum theoretical temperature drop that would bring the collector loop temperature down to the temperature of the tank. The user is then able to input the solar storage tank size and losses at maximum temperature in order to calculate the losses associated with the solar storage tank.

Whilst the practitioner is able to physically represent the system in terms of the size and orientation of the solar hot water panels including angle orientation, pitch and storage tank losses, there are drawbacks with other efficiency factors required for the input parameters. It can be concluded that by simply inputting a conversion efficiency ratio and heat loss coefficients, the algorithm is not modelling the dynamic characteristics of the solar hot water system, as described previously, because the efficiencies cannot be determined a-priori, it is the simulation itself that should provide these parameters if it were truly dynamic.

System configurations within the solar storage are also fixed assuming the solar water collector loop is connected to one separate solar storage tank. In some configurations the collector loop might be connected in conjunction with a twin coil system in a storage vessel, one providing for the solar hot water loop and the other by means of a gas fired or electric heating element. There is no obvious way of calculating the system performance of that type of system which is becoming popular with practitioners due to the limitations associated with plant room sizes.

Further limitations within representing the physical system itself are also prevalent, for instance if the user wanted to use the solar hot water to feed an air handling unit through a desiccant wheel, this would prove to be impossible to model, or if the heat was to be stored in a swimming pool the calculation and simulation would be found wanting. The system does not allow the user to select the type of system e.g. flat plate or evacuated tube. Whilst some of the differences associated with a flat plate or evacuated tube system can be captured in the efficiency ratios inputted by the user, some of the power associated with pumping and drain back facilities cannot be captured. For instance if the solar fluid within an evacuated tube system were to become dangerously hot, most solar panel systems have a function to automatically drain back the panels to ensure the system does not overheat. Control functions like this as well as frost control measures will affect the performance of solar panels (particularly in extreme conditions) and there is no current way of simulating this type of behaviour. The tool therefore can provide a rough estimate of the energy savings associated with a solar thermal hot water system however does not have the ability to model a solar water system in a detailed, dynamic way and is based on conversion efficiency rates, having fixed parameters in terms of system configuration.

Future simulation capabilities must therefore be able to rely less on inputting conversion efficiency rates and put more emphasis on modelling the solar thermal panels in terms of their operational behaviours including control aspects. Furthermore, there should be future flexibility in specifying solar thermal systems and their ability to store energy, not only with regards to having a tank attached to the system, which should have more functionality to allow different types of storage tank systems, e.g. single coil or twin coil, but also if the user wanted to use the solar hot water in a desiccant air handling unit system or similar.

3.3. Control systems

All of these commercial tools need features for the future in relation to smart grids, cascade control, intelligent control and many other types, such as then ones illustrated in Figures 8 & 9. Based on an initial review of the user manuals, the majority of commercial codes cannot incorporate the non-conventional control types in relation to heuristic, simulation based, and responsive controls. This leaves the review of conventional controls to be considered, and even in this area, the tools are to be found somewhat wanting, consider the case of optimum start/stop control.

Scenario simulation 7 – Optimum start control strategies

Design intent

As part of the upgrades of boilers for the retrofitting of houses the practitioner wishes to assess and model the effects of implementing an optimum start control strategy associated with the heating system.

Vendor claim #64

Commercial tools are able to model control algorithms such as control set points, optimum start and frost protection.

Optimum start principles

Typical control algorithms that exist for heating systems within buildings include optimum start/stop control; this is an algorithm that is able to determine the minimum amount of time required to bring the building to the desired temperature set-point, prior to occupancy.

How the programs perform

Most simulation programs have sections related to this type of control in the user manual, although they are very brief and unclear. They also have the interfaces to include for this as a "tick-in-the-box" style solution. In order to simulate this type of control system, often the tool will ask the user to specify a constant or variable set point of the controller that can vary in accordance with an absolute profile. In this case, the commercial codes recommend the user to attach a controller to more than one node. For the case of optimum start there could be a setup whereby there are multiple controllers in multiple zones to measure temperature within each step as well as a sensor that measures the ambient outdoor temperatures to inform the optimum start preheat period. So whilst the programme is able to have some degree of control with regard to optimum start, there are a few areas that are unclear as to how the code might tackle these issues and they are as follows;

1) The optimum start algorithm is based on a variable set-point i.e. the user specifies the time required for the pre-heat period to take place. There is no indication of how the software would be able to automatically calculate the time required for the boiler to switch on/off before the zone temperature meets the required set point which is dependent on outside weather conditions. In the extreme winter cases the boiler will take longer to reach temperature compared with the milder winter cases.
2) Thermal mass is clearly an issue for how long a room will be required to reach temperature set point and whilst some commercial codes state that they can account for the effects of thermal mass, it is not clear how the optimum start algorithm would include for this type of issue when preheat periods are required to be defined by the user.
3) Thermal inertia within the boiler systems is also unclear and this again will cause lags in the time required to meet temperature in the boiler itself. Furthermore referring back to the systems representation of boilers, there is no explicit way of representing the boilers' operational characteristics and users are required to make estimates to derive and establish their own parameters (Bannister, et al., 2011).

It is therefore clear that whilst there are some ways of simulating and getting round the issue of optimum start control there is still a long way to go before commercial codes can actually represent all of the issues that affect optimum start, especially when looking into non-conventional heuristic control that includes adaptive optimum start where the system is able to learn from the behaviour of the building to improve performance. Birtles and Jon describe a way of controlling optimum start algorithms through the use of their algorithm BRESTART (Birtles, et al., 1985), in this case it is shown that as outdoor temperature increases, a preheat time of a logarithmic nature is better than a linear type. These types of algorithms incorporate a form of self-learning, adaptive features based on outdoor temperatures and zone temperatures in the building. It is this type of system that commercial codes need to be able to model and, at present, it is very difficult even to begin to attempt and model something that represents the complexities involved in optimum start control from the issues described above.

Commercial codes have been claimed to be fully integrative and able to assess various configurations of HVAC control systems however from the case studies carried out and reviewing of user manuals it has been found to be lacking in areas. In relation to conventional control the codes are unable to take on board the effect of thermal inertia and start up times associated with optimum start stop. Furthermore, the adaptive nature of building control is unable to be represented in building simulation. In the case of nonconventional control, the functionality of programs does not encompass this type of control in commercial codes, the only way this could be achieved by practitioners is in the case of trial and error and simulating different design conditions based on an iterative process that is both tedious and time consuming. It is therefore imperative that the future of commercial codes are able to import adaptive algorithms that take on board this intelligent control aspect as well as performance issues associated with control response, like thermal inertia for start-up times.

3.4. Sustainable communities

This category addresses the ability of current commercial tools to adopt issues that relate to community energy systems, which includes the likes of district heating systems, demand side management and response, microgrid developments, electricity storage in the built environment, urban canyon heat island effects and emission streams in cities. Currently, the commercial tools do not yet have the capability of explicitly representing the different types of large scale heating systems and demand side management systems.

The simulation issues associated with sustainable communities are to do with extending the buildings to multiple buildings and external features (access to the sky vault and, vegetation etc.) this comes together well in the following scenarios that are addressed.

Scenario simulation 8 – Use of district combined heat & power

Design intent

The practitioner wishes to assess the integration of a CHP community district heating scheme within the development for both school and housing developments, the school has a swimming pool and wishes to use this to store some of the excess heat.

Vendor claim #11

The ability to assess renewable energy systems such as CHP.

CHP principles

In order to assess and appraise commercial codes in the field of CHP modelling, the different types of CHP must be established. These types can be broken down into the following categories:

1) Industrial CHP;
2) Packaged and mini-CHP;
3) Micro CHP;
4) CHP with district heating.

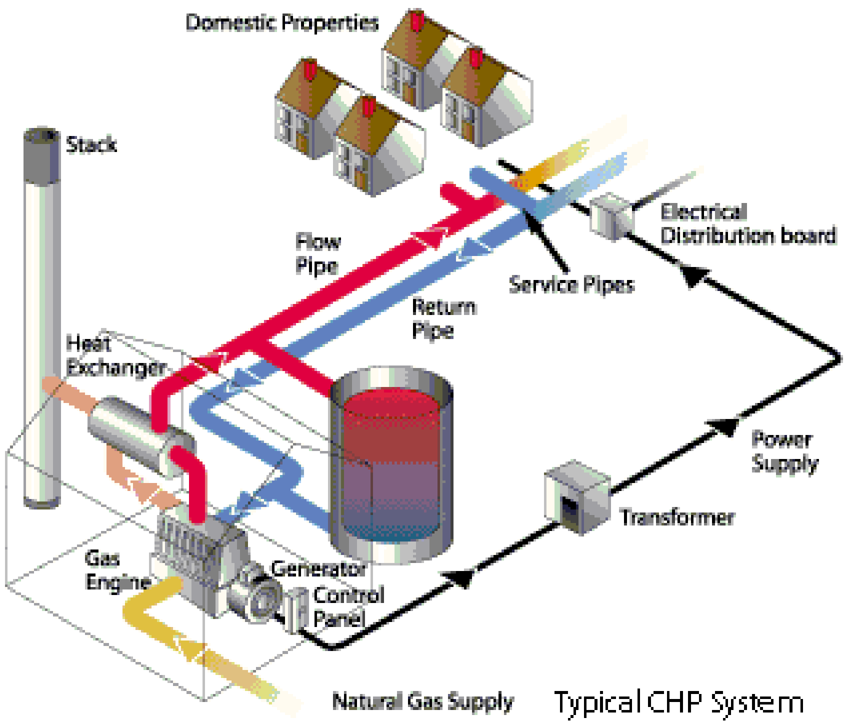

Figure 22 Typical district CHP system (PPSL, 2014)

For the purposes of this exercise, the CHP using a district heating scheme is required for analysis with the ability to store the excess heat in the form of a large heat sink – in this case a swimming pool. Figure 22 represents a typical community-wide district heating CHP system. Characteristics of the system such as the furnace boiler, fuel type for the compressor and turbine characteristics are all required for simulation purposes. The proposal is that the exhaust gases from the turbine can be used as a sensible heat source to reduce the heat input associated with the steam boilers provided for the district heating scheme. So, details associated with the gas flow rate required for the gas turbine should be incorporated in the model, heat losses associated from the heat exchanger should also be provided in order to calculate total net heat required for the heating of gas as well as the steam boiler characteristics for the site wide heating demand. The ability to store energy within the swimming pool is required, this in effect will be a heat exchanger within the pool, so the characteristics of the pool must be addressed, e.g. volume, temperature, size etc.

How the programs perform

The interface within commercial codes requires the user to input various parameters related to CHP performance. Once these input parameters have been set, the user then must create a time profile to dictate when the CHP unit will try and match the heating load. This parameter is usually set to "on continuously". Whilst typically CHP units are used to match heating load profiles, commercial codes should address the issues of matching operation to power load profiles, or perhaps a mixture of both, currently the codes do not have the facility to operate in this manner.

Other limitations associated with the modelling of CHP systems involve the inclusion of having a buffer vessel attached to the system for storing heat, typically this is considered good practice for CHP systems as the source of heat will be constant and otherwise wasted when the demand for heat is low. Other means of storing energy would be through, and in this case is, the use of swimming pools however there is no indication of how this could be achieved or even a way to simulate this in an abstract way.

The user must enter the fuel type associated with a CHP system, this ranges from gas to biomass fuel types however, there is no function to look into fuel cell or Stirling engine CHP systems. Once the system has been chosen, the performance parameters at maximum and minimum output conditions must be specified. These input parameters include the heat output as well as the thermal efficiency (heat output divided by energy content of the fuel) and power efficiency (heat output divided by the energy content of the fuel burnt). Presumably the tool then ramps this unit up and down accordingly between maximum and minimum output conditions in a linear extrapolated way, however this method in reality may not reflect the dynamic performance of a CHP system.

From the complexities described in the proposal there is no way that the gas turbine, the steam boiler systems, the distribution of heat to individual homes, and heat storage within the swimming pool can be simulated. In this aspect the commercial codes cannot deal with these types of systems and perhaps are better served for micro CHP systems. Future simulation capabilities of commercial tools must therefore incorporate: the functionality to address multiple buildings for the likes of district heating schemes, the ability to store energy through the use of buffer or swimming pool systems and improve the simulation algorithms, relying less on thermal conversion efficiencies, improving on match loading to power profiles and not just heating profiles.

Scenario simulation 9 - Electric storage boiler for demand side management

Design intent

The practitioner wishes to specify electric storage water heaters in the new build housing developments. Coupled with this, is the installation of a microgrid structure that includes the installation of wind turbines, battery storage devices and electric hot water storage system to store energy in the event of the demand for power being low. This is similar to projects such as the NINES project in the Shetland isles, as illustrated in Figure 23.

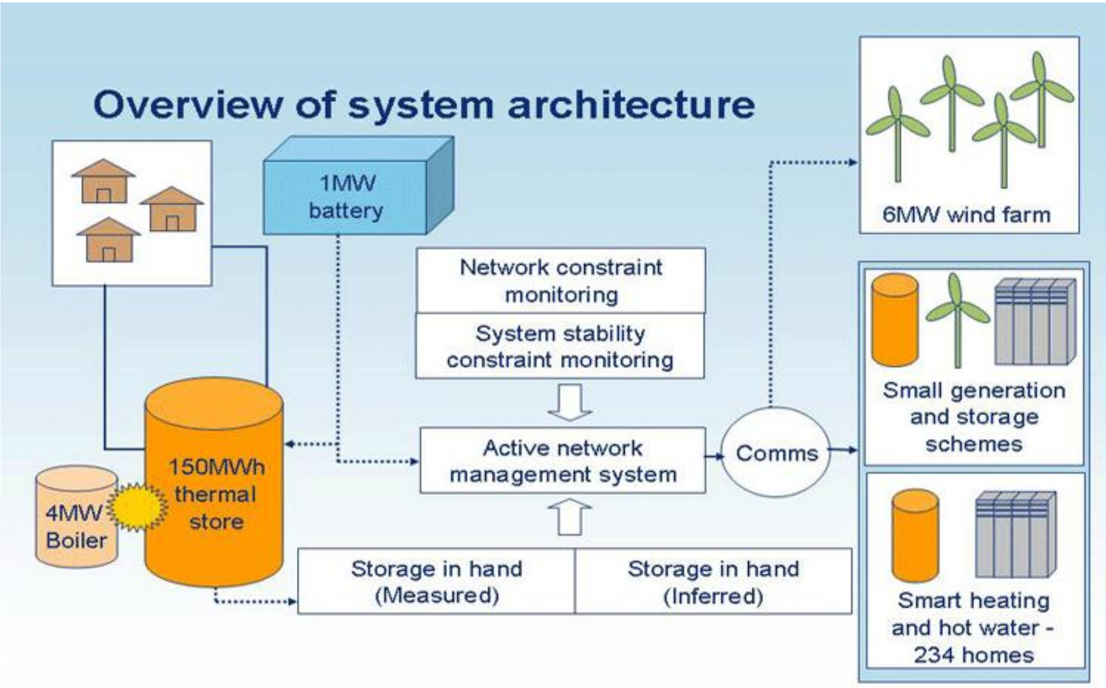

Figure 23 System architecture of a demand side management system (SSE, 2009)

Vendor claims #11, #26, #48

The ability to model hot water storage systems and the ability to model wind power systems.

Demand side management system principles

In order to effectively understand the principles behind demand side management there must first be the understanding of both the systems consuming energy, and the systems providing the energy. In effect, this system operates in the same way that a microgid system works. The model must therefore have the ability to model a wind turbine which would include turbine hub height, orientation, turbine type, nominal power, power factor, swept area and power output curve based on speed. This would then allow the commercial code to calculate the power output at any given speed.

Now that the supply has been configured and the demand profile has been set the tool must be able to compare the supply with demand and figure out the deficit associated with any surplus energy generation. In this case, the first port-of-call would be to store this excess energy into the hot water electric storage heaters within the new housing development. Any excess electricity can then be exported back to the grid or stored within the battery devices. So the practitioner must now determine the supply/ demand deficit and power flow associated with generation, storage and exported energy.

How the programs perform

Within the commercial codes industry there is an ability to model hot water storage heaters in a similar fashion to the hot water boiler systems. This can either be achieved in the form of a two staged boiler system either sharing the load equally or split in a variable staged manner. A boiler efficiency curve is entered and is then used to calculate the performance of the system at each time step. Hot water supply and return temperatures are then inputted as well as parasitic power consumed by forced fans, fuel pumps, stokers and/or draft. The tool has the ability to connect to the system an air source heat pump or a CHP unit to the boiler loop, this requires the practitioner to determine the proportion of load that each technology would supply and the temperature rise that would be experienced across the system. The codes however do not have the functionality of linking up a wind turbine to the electric storage heater.

Additionally, when it comes to analysing the effect of a wind turbine, the user is able to input parameters such as the hub height, the rated power in (kW) and the power curve from five points between 0 and 25 m/s. This provides the user with a basic understanding of how the wind turbine operates but there are still, essentially, some missing aspects that affect wind turbine performance, such as, if it is in an urban or rural area, orientation, turbine type and power factor. Furthermore there is no way of analysing the power flow characteristics, the comparison of surplus generation and options to address how this would interact with the electric storage heater, therefore the commercial code in this sense are not able to effectively model the integration of electric storage heaters with renewable technologies such as wind power.

The ability to export electricity back to the grid or store this into the likes of a large battery network is also found to be lacking as the power flow characteristics within an LV distribution network are simply not covered in the commercial codes. Therefore, demand supply management systems at a community-wide scale is simply unachievable for practitioners to assess and steps should be taken by commercial vendors to help achieve more functionality in this regard. Improvements can be achieved by ensuring that power flow characteristics are added to the functionality of software and therefore the balance between energy generated, consumed and exported, at a community wide level, can be better represented.

Scenario simulation 10 – Urban heat island effects

Application intent

The practitioner wishes to assess the cumulative effects of the community with regards to the impacts that the new build developments will have on the urban environment in relation to the urban heat island effect.

Vendor claims #12, #13

The ability to assess the impact of the urban heat island effect, right to light of building and surroundings, exterior wind effects, pedestrian comfort and pressure envelope.

The urban heat island effect principles

The urban heat island effect is essentially the condition where outdoor air temperatures are significantly higher due to the effect of urbanisation, this can typically be seen between city centre and rural areas. What issues must be addressed in order to examine this impact? There are many factors that influence the heat island effect in a temporally and spatially varying way and they include the following:

1) Climate;
2) Topography;
3) Physical layout;
4) Short term weather conditions.

A more detailed variation of this is summarised well in Table 6.

Table 6 Factors affecting the urban heat island effect (Oke, et al., 1991)

Factors affecting heat island effect	Description
Canyon radiative geometry	This is the reduced long wave radiation loss form from street canyons as a result of complex interchanges between buildings and the screening of the skyline.
Thermal Properties of Materials	This may store up sensible heat gains in the fabric of the community during daytime occupancy and be released in the night. Also due to the use of asphalt and concrete the ability to dissipate heat through evaporation and plant transpiration is reduced.
Anthropogenic heat	The heat released by fuel combustions of mobile and stationary sources as well as heat from animals/humans
Urban greenhouse effect	The effect of an increase in long wave radiation from pollutants within the urban atmosphere
Canyon radiative geometry	The effect that decreases the albedo of the system due to multiple reflection of short wave radiation by canyon surfaces
The reduction of evaporative surfaces	This results in more energy in sensible heat than in latent heat
Reduced turbulent transfer of heat from within the streets	-

Therefore, these following factors must be addressed in order to determine the impacts that the community has with regard to the urban heat island effect.

How the programs perform

From assessing the user manuals, there is the ability to represent a community of buildings by importing a model as will be discussed in simulation scenario 14. In this case, the model will include for topographical components and local shading resulting from trees and other buildings. The physical layout therefore and topographical data is compatible with the commercial codes and this, coupled with weather data, gives the user all of the information they require. However, the issues start to build up when looking at how to model the heat island effect in further detail. Firstly, it can be accepted that theoretically all surfaces can be assigned materials, the issues however become problematic when the model must take on board the likes of vegetation and trees as these material properties and interactions become a lot more complex to model as has been described previously in simulation scenario 2 (green roofs and PCM's).

There are other issues associated with anthropogenic heat build-up. Whilst the programs can model, in a simplified way, the energy and heat generated by the likes of CHP systems, boilers and air source heat pumps, it is difficult to model the resulting heat output as a result of these thermodynamic processes. For instance, in order to overcome this problem with regards to air source heat pumps, the practitioner must evaluate how much energy the heat pumps are using at any given time and so the cooling load is established. Therefore, on the condenser side, the practitioner can establish the portion of heat that is emitted from such condenser and then multiply this load up by the amount of buildings within the confines of the community/city. This crude method of establishing the anthropogenic heat build-up can then be applied to other technologies such as the boiler and CHP loads (which in some cases will reduce these emissions). This arbitrary method of calculating community anthropogenic heat loads, would give the user a very makeshift figure to assess the urban heat island effect but in no way would it be spatially and temporally varying or even remotely accurate.

The future functionality of commercial tools must therefore incorporate the evapotranspiration properties associated with vegetation and trees that are typically found within the community. Furthermore, simulation must take on board the nature of anthropogenic heat build-up from energy systems as a result of thermodynamic processes to truly assess the dynamic, spatially and temporally varying nature of the urban heat island effect.

3.5. Comfort

Commercial tools require features to assess performance assessment methods. Currently there are no standardised ways to undertake performance assessment. There is also a lot of mix and matching between different concepts that are inappropriate and outdated, for example PMV, which is a steady state concept, is considered when the world is dynamic. Codes are not often clear on the criteria to assess comfort parameters, for example, often commercial codes can give good radians diagrams however the user is unable to establish what effect this has on visual comfort. Furthermore, there are tables that are produced in commercial codes that give out energy balance data such as kWh and power load profiles, however there is no way of assessing the balance of energy, the table just contains energy data, and so there are no semantics to address these issues. The following example scenarios were investigated in commercial codes to test these theories.

Scenario simulation 11 – Thermal comfort analysis

Application intent

As part of the extraction of results for the analysis of the natural ventilation strategies in the development of the new school building within the community, the practitioner wishes to assess the thermal comfort within the building for one of the classrooms. As part of this assessment the user wishes to understand if this environment, full of people, will, for a reasonable amount of time, feel comfortable.

Vendor claims #17, #30

The ability to assess indoor/outdoor thermal comfort.

Thermal comfort principles

In order to address this performance domain, there are various parameters that the user must understand to effectively simulate it. The first parameter that must be understood is occupancy. In this instance the building will have different amounts of people entering and leaving the classroom during the period of a day, with dissimilar states of activity, some of them sick with different requirements and so the first method of determining thermal comfort is to address the model with a suitable occupancy profile. Secondly, the user must determine the factors that affect thermal performance which are spatially and temporally varying and these can be defined as shown in Tables 7 and 8.

Table 7 Personal variables affecting thermal comfort

Item	Personal Variables
1	Activity
2	Clothing
3	Age
4	Gender

Table 8 Physical variables affecting thermal comfort

Item	Physical Variables
1	Air temperature
2	Surface temperature
3	Air movement
4	Humidity

Therefore, in order to effectively determine the thermal comfort of occupants, the user must address each individual in the room, the activity rates that are occurring, the age of the occupant, the gender etc. Once this has been established the physical variables can be determined. For the likes of air temperature there are various categories that fall under this domain including those described in Table 9

Table 9 Air temperature categories for thermal comfort (McMullan, 2007)

Item	Type	Definition
1	Inside air temperature	the average temperature of the bulk air within the room measured by a dry bulb temperature
2	Mean radiant temperature	the average of effect of radiation from surrounding surfaces
3	Inside environmental temperature	a combination of air temperature and radiant temperature
4	Dry resultant temperature	a combination or air temperature, radiant temperature and air movement.
5	Room centre comfort temperature	is a combination or air temperature, radiant temperature and air movement.

Air movement is a parameter that affects thermal comfort, areas that are most sensitive to people include the back of the neck, ankles and the forehead. Therefore, the distribution of draft, and its reference point to the occupant, is an important issue for consideration, as well as air movement that is caused by convection currents. It is important to address where to measure different temperatures, for the purposes of this assignment thermal comfort may differ in a desk situated next to a window than compared to a desk in the centre of the room. All of these factors need to be addressed when assessing thermal comfort. The tools often bombard the users with different categories of information but it is the user who must decipher this information, with great difficulty, to get to the critical issues that affect thermal comfort and so commercial codes could be better at clearly separating and defining this criteria.

PMV/PPD is a method that was developed by Fanger which was based on steady state laboratory experiments carried out in the '50s (Luckiesh, et al., 1949). This method predicts the thermal comfort of individuals based on the survey results relating to the predicted mean vote and/or the percentage of people dissatisfied (PPD) index. This index uses the combination of six factors affecting thermal comfort and a seven-point scale ranging from -3 (cold) to 0 (neutral) to +3(hot) (ASHRAE, 2004). It is considered incompatible for users to use the PMV/PPD index for dynamic simulation therefore the user must determine other ways to truly assess thermal comfort.

How the programs perform

As part of the review of commercial codes, a model was created to represent a typical classroom. In order to address thermal comfort the occupancy had to be first set. Within the commercial code, the user could specify a prescription of heat gain by inputting 50 people at 95 W each from 9am to 5pm. However, going into further depth, the establishment of the true representation of occupancy proved to be difficult. The user could specify certain comfort parameters based on personal variables such as a clothing level of 0.69 clo, an activity rate of 90 W/m^2 and an air speed of 0.10 m/s. However, the software could not take on board the variability of these factors such as clothing levels, age ranges and activity rates of each person, and also how these variables might change seasonally from summer and winter.

If the user wanted to specify different activity rates of the pupils with some being seated at work and others walking around, which is becoming increasingly more popular in educational facilities with multi-functional classrooms, the user could not establish this kind of level of detail in an occupancy profile. Therefore, it can be deduced that commercial codes cannot assess an individual's response to changing clothing or activity levels in accordance with outside climate conditions because these factors were fixed variables, set for an entire year in a post-processing mode during the simulation of results.

It is also worth investigating the various locations of people within a room and how this might affect thermal comfort. The tool, in this instance has a CFD program that can be run which allows the user to obtain a snapshot e.g. a typical winter and summer day of the distribution of either temperature, velocity, pressure and PMD/PPV over a certain time period. The commercial codes are limited in the way that the CFD model is configured, as it is feeding in boundary conditions from the first dynamic simulation and taking temperatures at those boundary conditions and simulating it, finishing it, and then moving on to the next time step using Cartesian grid coordinates. The state of the art in CFD is based on selecting the appropriate turbulence models and establishing how they would vary and how they would be configured, decoupled from the original dynamic simulation. Furthermore from the simulations carried out in scenario 4 for natural ventilation systems, the tool must be able to address the abilities to take on board the distribution of draft as mentioned previously, due to the constraints involved in modelling these issues, the ability to model thermal comfort within a space is further compounded.

It is therefore important that, if a simulation is being carried out under these conditions, the user is made aware that this is based on a static fixed condition and not under a dynamic simulation consideration. Furthermore, the simulation is based on occupancy models that are static and not dynamic, the differences in opinion on thermal comfort is not encapsulated, the variation in clothing rates based on season is also not considered and furthermore psychological conditions associated with thermal comfort cannot be considered. The simulation process therefore requires a realistic dynamic model of occupants that takes on board these factors to give a realistic value of PMV/PPD. Other areas that are lacking in commercial codes are related to the distribution of draft and the techniques used for carrying out CFD model simulations. Indeed it has been shown that Fangers approach to thermal comfort does not include the climatic adaptation which suggests that physiological experiences and occupant expectation will have an effect on what users define as comfortable. Secondly, it does not take on board the additional measures that occupants might use such as fans, shading, or adjusting activity levels to address comfort levels (Huws, et al., 2013)

Despite the simulation program offering very colourful maps of temperature, velocity, pressure and PMV/PPD distribution, the quality of these parameters are somewhat questionable and also the inputs due to the static nature of clothing levels, activity rates puts further reduction in the quality of the distribution of the results. It is also absurd for the user to assess the distribution of PMV/PPD as it is a steady state concept. The user must therefore filter through the parameters to obtain distributions associated with mean radiant temperature and all of the other parameters that were depicted in table 9. It is therefore considered to be very difficult for practitioners to extract the relevant data and furthermore the authenticity and quality of the results that are contained within these models are somewhat questionable and unreliable for predicting thermal comfort.

The future capabilities of commercial tools must therefore improve in their ability to model the dynamic nature of occupancy, the point of reference and method for assessing thermal comfort, perhaps by providing the user with a step-by-step guide and an integrated view of performance rather than the user having to extract this from simulation, details of this integrated view of performance are described later in the following scenario.

Scenario simulation 12 – Visual comfort analysis

Application intent

As part of the new school development the user wishes to look at visual comfort within the classrooms, taking on board the effect of daylight and energy efficient LED lighting.

Vendor claims #22, #36

Commercial codes have the ability to assess daylight and artificial lighting simulation, and visual comfort including daylight, views and glare.

Visual comfort principles

In order to effectively model visual comfort, there are aspects within building simulation that must be taken into account. An obvious example of this is an office that is insufficiently lit and can cause an occupant to strain the eyes. There are however other aspects of visual performance that also affect visual comfort and they are described below in Table 10;

Table 10 Aspects affecting visual comfort (Salvendy, 2012)

Aspect affecting visual comfort	Definition	Variables determining aspect
Flicker	A light source that varies in brightness over time	Frequency and percentage modulation of the oscillation in light output. Proportion of visual field over which the flicker occurs Adaptation luminance
Glare	Disability glare – light scattered in the eye Discomfort glare – annoyance caused by high luminance in the field of view	Intraocular light scattering, room size and shape, room surface reflectance, illuminances, luminaire characteristics, number and location of luminaires, luminance of the entire field of view, observer location and line of sight, difference in individual glare sensitivity
Shadows	Light is intercepted by an opaque object. E.g. large items of machinery/furniture casting shadows affecting light levels.	Proportion of interreflected light space and the location of adjustable local lighting.
Veiling reflections	Luminous reflections from specular or semi-matte surfaces that physically change the contrast of a visual task	Specularity of material being viewed and the geometry between the observer, target, and any sources of high luminance.

It is clear that there are many factors that affect visual comfort and there have been many attempts to create a criteria that assesses this. For example, in the instance of glare, there are a number of systems used to evaluate the intensity of it, such as; VCP (visual comfort probability, UGP (unified glare rating) and DGI (daylight glare index) (Hirning, et al., 2013). Another criterion that was developed is the use of the Guth index, which is a probability index rating developed in the late 40's using laboratory experiments and surveys (Luckiesh, et al., 1949). Whilst this method gives an indication of comfort it is a steady state concept and does not relate to the dynamic, non-linear, stochastic nature of reality.

How the programs perform

In order to assess the codes, as part of the investigation, a mock model of a classroom was created and assigned various lighting fixtures and glazed openings. The model functionality was then tested and the following points observed.

Within commercial tools there is the ability for the user to select what type of sky conditions might be expected e.g. sunny/intermediate or overcast and a simulation can either be run for a typical day or 12 design days over a 12 month period. Then the user must select the eye viewing position within the room using X, Y, Z coordinates. Surface properties of the internal partitions can be selected from a library database which includes either metal, plastic or coloured parameters and each material has a parameter summary detailing the Rr, Gr, Br, Sp and Rgh parameters. This allows the solver to calculate the reflectance of the internal surfaces. The user also has the flexibility to enter in components such as furniture and other sources of internal obstructions which will have effect on shadow, glare and light in accordance with the surrounding environment. Once the parameters associated with impacts on the internal visual environment has been specified, the simulation can be run and the results obtained.

In the instance of examining glare the user is able to address this by examining the CIE Glare index which is the standard to evaluate discomfort glare and Guth visual comfort probability (percentage of people satisfied) within a room. The Guth index is a vector integration of the luminance in a person's field of view, weighted by psychological conditions and so, as an index, if it's less than a certain value, then it will have a bad effect for visual comfort for the occupant. This index however can only be simulated at one particular point in the room for one particular person and is objective (based on results from surveys). A better and surely more robust means of calculating the impact of glare for a classroom of 30 people would be to calculate discrete angles and consider what the worst case would be and what direction of view would correspond to the worst case of glare. In this way design considerations could be made quickly to determine which way a desk should face and inform the design team at an early stage to ensure that furniture is positioned in the best possible, visually unobtrusive way. Currently, there is no means within commercial codes to carry this out other than through the laborious and monotonous way of sensitivity analysis. It is worth noting that while the Guth and CIE glare index take on board different viewing angles for glare as illustrated in Figure 24, it does not carry out a comprehensive analysis for every point in the room and for every person, it is also worth mentioning that these indices to do not take into account the entire visual field and so new methods have been adopted that take on board this factor (Kim, et al., 2010).

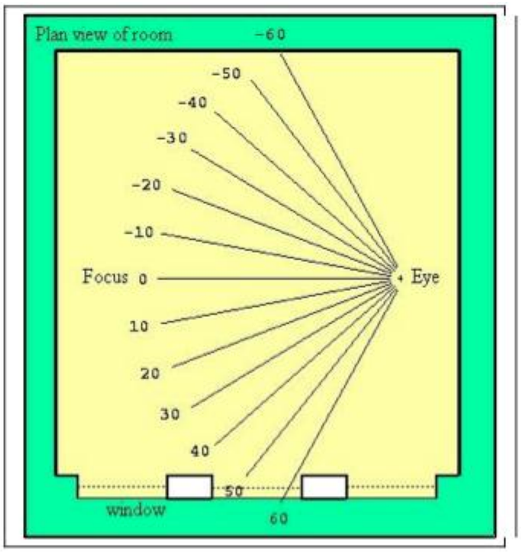

Figure 24 Calculation of CIE glare index

It is also worth assessing the way in which visual comfort can be displayed in commercial codes. The current state-of-the-art research examines how information can be presented in the most effective way. For integrated views of performance there are many things that the user may want to understand and it is important to convey this information as best as possible. Studies have shown that the least effective senses for humans is vision and taste and the most effective senses are the kinesthesis type, followed by touch and auditory (Prazeres, et al., 2006). Therefore, it is important to address the perceptualisation techniques of building simulation results and not rely on data visualisation alone. Within the esp-r system for example, an integrated view of performance has been developed which is a standard set of performance metrics used to display multi-variant views of performance as shown in Figure 25 below (Clarke, 2001).

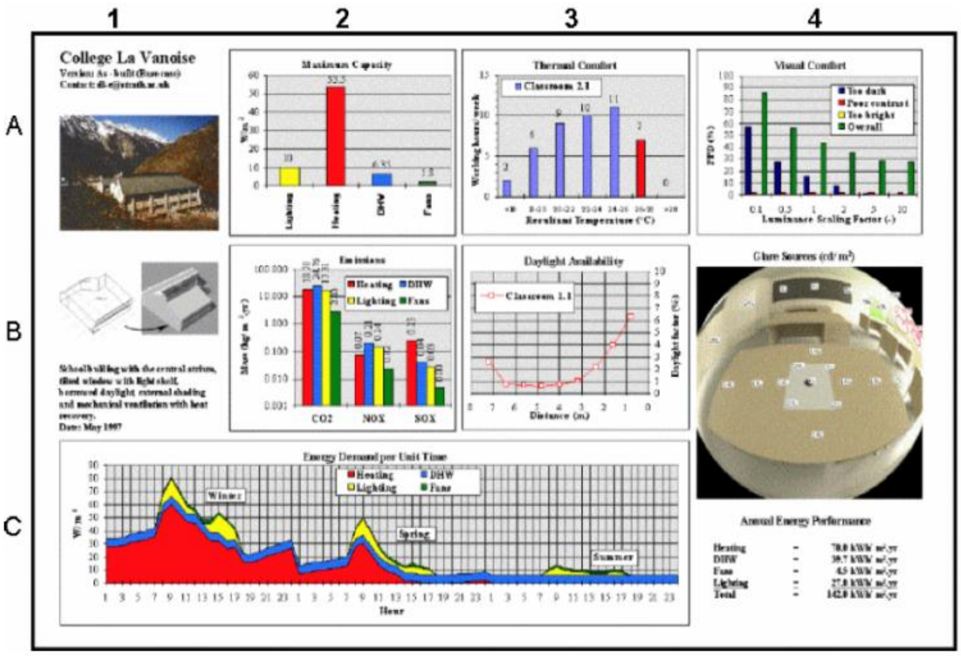

Figure 25 Integrated performance view (Clarke, 2001)

Furthermore, studies have gone into further depth in relation to integrative views of performance and recognised that different users require different levels of information, in different formats. Through the development of the I^{2}PV tool, Prazeres was able to come up with a method of presenting summary data, drilling down data presentation to explore performance in detail and allowed for the selection of a communication style that best represented the type of user (Prazeres, et al., 2006). An example of this drill down structure is shown in Figure 26 with various parameters associated with visual comfort including a three dimensional view of glare for the selected zone highlighting any issues or areas of concern, audible warnings to alert the simulator of any issues, indication of Guth index values for two opposite directions and many other options that will give an overall view of performance with respect to the visual comfort domain.

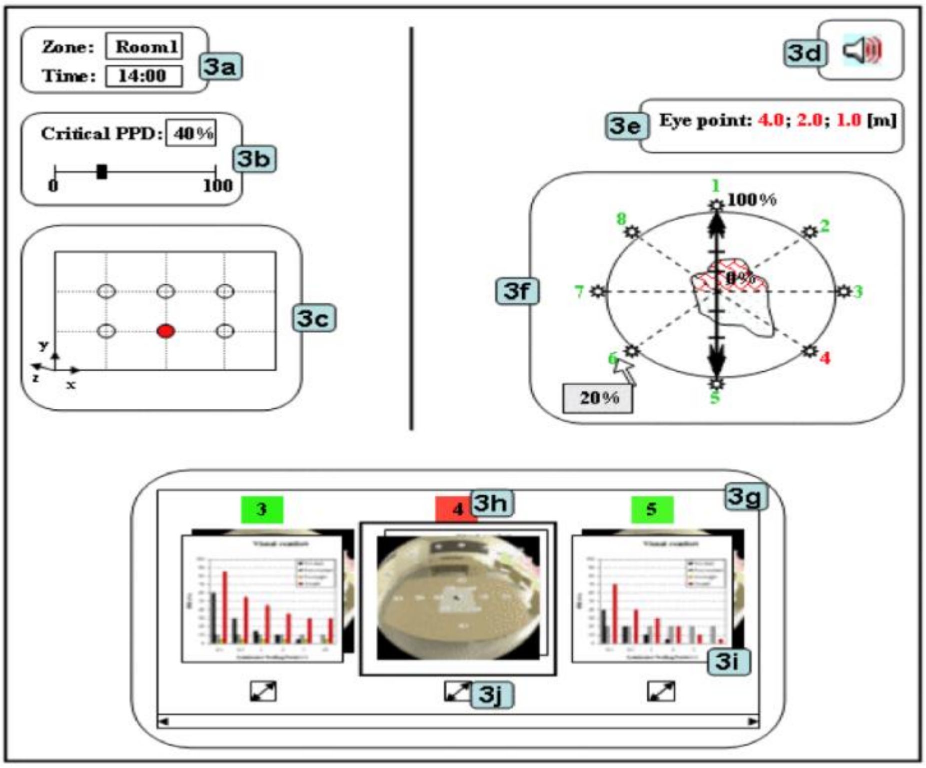

Figure 26 Visual comfort and glare performance view (Prazeres, et al., 2006)

Currently, within commercial tools there is a lack of this type of integrated view of performance, and in most instances, the user is required to extract all of the different factors associated with visual comfort. This is all dependant on the user's perception of what might be required so clearly, having a standardised format to display this multivariate performance issue, would minimise the margin for human based error in evaluating comfort parameters and enhance the effectiveness of commercial codes.

In terms of the performance domain of visual and thermal comfort there have been various issues related to the objective nature of comfort parameters such as the Guth index and the PMV/PPD methods that have been highlighted. It is therefore clear that commercial codes can and should improve in these areas to derive truly dynamic and accurate representations of thermal and visual comfort. In the case of visual comfort whilst the commercial codes are good at carrying out glare calculations based on position, a better system would be for the simulation codes to determine where the worst cases of glare exist and so the reference point need not be static but positioned throughout multiple positons in the room for simulation purposes. Commercial codes should also move towards establishing a standardised, user-specific, integrative view of performance and not rely on the user to extract the relevant information from multiple data sets, such as the developments carried out and displayed in the I^2 PV tool. (Prazeres, et al., 2006).

3.6. Health

Commercial codes claim to be able to address issues that affect the health of users within buildings and to some extent CO_2 levels and some contaminants can be examined in further depth. However, due to the complex nature of indoor air quality and the many different types of contaminants that exist within a building, the amount of information and the accuracy of the results are quite difficult to simulate. Therefore, commercial codes must become more refined in these regards to truly take on board indoor air quality simulations, and so the scenario simulation below that exemplifies this, has been tested and scrutinised to support this theory.

Scenario simulation 13 – Indoor air quality assessment

Application intent

As part of the health of the occupants, the practitioner is required to assess the indoor air quality for the new and existing houses within the community.

Vendor claims #5, #18, #29

The ability to assess indoor air quality, condensation, contaminant dispersal, environmental quality and health.

Indoor air quality principles

Indoor air quality is an increasingly important issue to developers as it can affect the health and comfort of occupants. In order to effectively simulate indoor air quality there are a few parameters that must be considered.

Firstly, it is important to understand factors that affect indoor health, namely the pollutant, odour and particulate types. The pollutant types can consist of various gaseous types of pollutants such as: the build-up of CO_2, carbon monoxide, nitrogen oxide, nitrogen dioxide, sulphur dioxide, ozone and naturally occurring radon. Other issues associated with indoor air quality include odours that can emanate from: cooking processes, decomposing foods, sanitary appliances, soil and waste water drains, building materials and furnishings, and humans (via sweat etc.). These types of odours may be a mixture of volatile organic compounds, water vapours and odorous gases. Finally particulates are fine particles released by occupants, furnishings paints, coatings, aerosol sprays, dust-mites/insects and moulds. These biogenic pollutants can cause harm to human health in the form of: fungi, moulds, mites, bacteria, viruses and pollen. These health issues can range from lung irritation, asthma and allergic rhinitis (Bernstein, et al., 2008).

It is important to model the effects of contaminants within the room and also to model the effects of ventilation within the space including draft, natural and mechanical ventilation, as these processes will help to minimise the presence of all odours, pollutants and particulates. Some of these issues have been touched upon in the previous simulation scenarios such as natural ventilation and draft distribution, but for the purposes of this scenario, the user is more concerned about obtaining information related to indoor air quality within a room.

How the programs perform

With regards to indoor air quality, the user is able to assess the effects of natural ventilation or mechanical ventilation by inputting a prescribed window opening or design flow rate to ensure the continuous supply of fresh air, however, the distribution of contaminants within the air becomes a complicated process. Within the tools there is the ability to assess the percentage of CO_2 within a space and indeed when using CFD codes the practitioner is able to see the distribution of CO_2 within a room.

The problem is that the codes cannot provide a dynamic model of the occupants and so any distribution of CO_2 is based on static figures. Furthermore, there is no way in which the user can assess the distribution of the various gaseous elements within a room, this is perhaps quite a complex consideration as it will vary depending on the location and urban environment within which the building is situated. The health concerns associated with condensation and mould growth is another area that cannot be considered as has been mentioned in the simulation scenario 2 related to thermal bridging. There are also issues associated with the build-up of particulates from people and furnishings, as this type of information is not included in the commercial code platforms. So whilst the practitioner can assess a small amount of information related to CO_2 and ventilation within the spaces, there is no accurate way to carry out a detailed dynamic simulation of particulate, odour and gaseous contaminant build up within a room and assess the health effects that these distributions may cause to the users. The commercial codes can therefore only provide a partial view of indoor air quality related to health issues within a building.

It is therefore clear that commercial codes should improve in their functionality by allowing the user to assess the various types of contaminant dispersal, not just those related to CO_2. This would indeed help the user to then determine health related aspects of poorly performing buildings and mitigate any design decisions made early on in the project process.

3.7. Interoperability

Interoperability within simulation is the ability for commercial codes to exchange information and communicate with other simulation orientated programs.

In this case, it is expected that in the future, simulation tools will not only be interoperable with geometrical based formats but also formats that contain information on; other systems, controls, leakage distribution of a building, discretisation of CFD grids, topographical information based on web based servers, and many other areas. Furthermore, these models are being constantly updated and changed due to the multidisciplinary and progressive nature of building design and so need to be updated on a regular basis.

Therefore, it can be presumed that commercial codes are somewhat lacking with respect to this future target of interoperability. However, the commercial vendors do claim that they have the ability to exchange geometrical information between models and so the case study of simulation scenario 14 is used to test this theory.

Scenario simulation 14 – Interoperability, geometry & multiple zoning

Application intent

As part of development upgrade, the community is proposing for a new school to be built. The practitioner is required to model it, and has been issued with a sketch up model in an .ifc format and must produce a model with multiple zones that reflects this.

Vendor claim #1

Commercial vendors claim that the software is interoperable for most building modelling formats and are fast at producing these models.

How the programs perform

As part of the interoperability of tools the practitioner is expected to save an inordinate amount of time creating models from scratch by simply importing a pre-created, pre-defined model at the click of a button.

The testing method was carried out in the following way: an exemplar sketch up file was imported into one of the commercial code platforms. The file was very detailed and included three exemplar building models of a typical school campus with a large amount of geometrical detail. The file was created in the .ifc format, which is typical of a sketch up model. The file was then imported into the commercial code, however it was not a recognised file format, so in this particular instance the model could not be imported into the commercial code platform. Unfortunately there was no other way to receive a recognised file in a different format other than a dxf file. This dxf format did not include the full three dimensional model and only existed in a one dimensional format. This meant that the practitioner had to trace the room layouts for each floor and match this with architectural general arrangements and sectional plans.

This exercise proved that the software, in this instance, was not compatible with the commercial code and from reviewing online forums the recommendations were to try and receive the model in another format. Whilst it may be proved that other formats such as gbXml models are compatible, in this instance, the commercial code platform failed to be able to use this type of model and so did not meet the claims of commercial vendors.

In order to progress with this particular model the rooms were traced and constructed using the geometrical tools that exist within commercial code platforms. These generally give the user the ability to create rectangular or polygonal shapes to represent different rooms. After this the glazing was inputted and doors assigned followed by construction types. This process was rather time consuming and laborious. Once the constructions had been assigned and the model was created, the zoning requirements had to be established. Therefore, it can be deduced that the commercial codes, whilst in some cases, may be interoperable between other file formats, they still have some way to go and could do with being more robust in this area.

Within buildings it is often the case that different areas consist of different mixes of technologies occupancies and activity rates, for example, some rooms might consist of natural ventilation systems others might consist of mechanically ventilated systems and it is for these purposes that areas within a building must be zoned appropriately. The commercial code had the ability to group rooms by various types. In some instances, rooms were grouped by which floor they were situated, in others they were grouped by whether the rooms were mechanically or naturally ventilated and in other specialist rooms, such as wood working and metal working rooms, with specialist mechanical ventilation systems, were grouped accordingly.

This process improved the time taken later on in the stages to assign various heating and ventilation systems as the rooms could be assigned to these systems according to their group type without having to individually assign ventilation and heating systems accordingly. There are however areas where the zoning and geometry building process could be a lot easier. For instance, due to the nature of this particular model, there were an exhaustive number of rooms that each individually had to be assigned to a group type. Commercial codes, in order to live up to their claims of being fast and efficient at creating building types, would be better served by an automatic method to convert the likes of this 40,000 element poly surface model into groups that can express multi-zone thermal model geometry, occupancy patterns, space usage and materiality based on the information held within other specialist software models.

The results indicate that whilst simulation tools claim high levels of interoperability for geometrical, three dimensional models, as well as being able to quickly assign thermal zones, in the case of scenario 14, the tools were not able to live up to these claims and therefore should be more robust in this domain. Furthermore, commercial modelling tools have been found to be somewhat laborious and tedious when it comes to assigning multiple thermal zones. The future of building simulation is pointing towards a truly integrative and interoperable functionality that not only takes on board automatic geometry from three dimensional models but also interprets geometric surfaces and materials to define space boundaries and uses historical simulation settings to aggregate spaces into smaller numbers of thermal zones. This work is being carried out in the field at present and looks to further reduce the time required for building simulation as the issue of creating a model can be the most time consuming aspect of the simulation process (Greenberg, et al., 2013). Other interoperability issues that would link models with other specialist platforms are found to be non-existent, and the future of simulation must move toward a truly integrative interoperability with lots of different types of simulation software, not just the geometrical types such as sketch up and Revit.

4. Conclusions and future work

This thesis has scrutinised the capabilities of commercial codes, developed an insight into the requirements of practitioners for the future, sampled these in the context of a particular integrative case study and scrutinised the commercial codes modelling capabilities.

From the review it can be found that generally speaking the commercial codes are relatively good in the area of representing buildings in a geometrical fashion however, can improve when it comes to automatic zoning and interoperability with other programs. Furthermore, with respect to form and fabric, simulation needs to move towards a three-dimensional method of measuring transient heat conduction and mass flow paths in buildings, to take on board time adaptive materials such as; thermal bridging, green roofs and phase change materials.

From the case study scenarios carried out for the conventional and renewable supply systems, it can be demonstrated that in a lot of circumstances, whether it be: the modelling of boilers within a domestic heating system, the inclusion of; heat pumps, solar thermal or hot water circulation pumps, a performance curve or coefficient of performance is required to be inputted by the practitioner. This thesis argues that it is actually the simulation programs that should be able to determine the performance curve, COP values, system efficiencies of HVAC equipment at any given time, and not the user. This would ensure that the system parameters such as the boiler performance characteristics are being monitored in a dynamic way and not relying on a linear interpolation between efficiency points on a curve that the user has inputted, often based on manufacturers data which, in some cases, is overstated and unreliable. Therefore, the future of commercial codes must be able to model the behavioural effects of systems including purge losses, thermal inertia losses and other operational constraints associated with systems performance.

In the case of systems control, the codes were found to be lacking in the area of non-conventional control with heuristics and, in terms of conventional control, in the case of optimum start, the codes could not take on board the complexities attributed to this area, such as thermal inertia, start up time and intelligent start-up control. The future of simulation codes must therefore include for aspects that affect this type of control and the adaptive nature of smart controls.

From the assessment of case studies associated with community simulation there are areas where commercial codes could simply not simulate the effects of systems that might typically be found in a small community. This included the ability to model a district heating scheme for a small community, furthermore, the commercial codes lacked the ability to match these CHP systems with energy storage in the form of buffer vessels or sink heat sources such as a swimming pools. The similar requirement for energy storage in a demand side management system such as the NINES project in Shetlands, and as discussed in scenario 9, was not possible to simulate. The ability to model heat island effects accurately within a community was not possible and had to be done through an abstract calculation requiring the user to make simplifications and assumptions. It is therefore justifiable and reasonable to suggest that commercial codes cannot handle the assessment of sustainable communities and requires future developments to incorporate the impacts and parameters that practitioners will undoubtedly wish to assess, both now and in the future, as the move towards demand side management, microgrid and smart grid communities becomes more popular.

It has shown that these tools are not well found in the regard of thermal and visual comfort, as most of these measurements are based on steady state laboratory based conditions such as PMV/PPD and Guth Indices. Simulation needs to take on board the dynamic nature of occupancy and the varying levels of behavioural traits that can often vary from occupant to occupant. The tools could also develop better ways for communicating and displaying outputs from simulation, similar to the work that has been carried out by Prazeres in the form of integrative and interactive views of performance (Prazeres, et al., 2006). Furthermore, the tools, whilst able to assess indoor air quality with respect to health, cannot take on board the dispersal of other pollutants and contaminants and therefore steps towards this should be incorporated in the development for future capabilities of commercial codes.

An overall view of the way that commercial codes perform, in accordance with the scoring criteria previously mentioned, is summarised in Table 11.

Table 11 Scoring matrix of commercial codes

Category	Description	1. Cannot Handle	2. Not Very Well	3. Okay	4. Good	5. Perfect
Form & fabric	Specifying complex geometry					
	Specifying construction fabric properties e.g. glazing, walls, roofs etc.					
	Room contents such as furniture and machinery					
	Ability to model interpenetrating materials					
	Calculating dynamic heat flow in a three-dimensional sense					
	Measuring the effects of thermal bridging					
	Ability to model phase change behaviour in materials					
	Ability to model green roofs and evapotranspiration properties of materials					
Conventional supply systems	Boiler simulation					
	Natural ventilation strategies					
Renewable supply systems	Air source heat pumps					
	Solar thermal installations					
Control systems	Non-Conventional with heuristics					
	Conventional optimum start					
Sustainable communities	District CHP heating systems					
	Demand side management Systems					
	Urban heat island effects					
Comfort	Thermal comfort					
	Visual comfort					
	Acoustic comfort					
Health	Indoor air quality					
Interoperability	Geometric interoperability					
	Interoperability with other specialist platforms e.g. CFD platforms					

As part of this thesis, a wide range of simulation scenarios have been appraised to inform the reader of the future requirements of commercial codes for practitioners but there are many other areas that could not be considered and this should form part of any future investigations. This includes;

1) Analysis on how well commercial codes can deal with building related costs.
2) Study on how commercial codes can adopt some of the algorithms and functionality that research codes provide and bridge the gap between the two.
3) Assessing a suitable means for measuring visual, acoustic and thermal comfort in dynamic building simulation

4) Analysing perceptualisation techniques and its functionality within commercial codes.

There are a lot more areas in this field that can be explored in order to improve simulation and ensure that it meets the requirements that practitioners will be faced with in a future where buildings become more arbitrarily complex and the performance aspects of buildings becomes multi-faceted and complex. This thesis has provided some insight into the future developments required for commercial codes and provided relative measures to ensure that the future of building simulation evolves and becomes an even greater aid for the building simulation practitioner.

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Appendix A – Structured interviews

As part of this thesis, structured interviews were carried out with interviewee 1 and 2. The detailed results of which are reported in this appendix. The interviewee's have requested for their identities to be kept anonymous however it can be stated that interviewee 1 is from an architectural background and interviewee 2 is from an engineering background. In each interview the host gave a background of the purposes for this interview in relation to current and future requirements of practitioners in the field of building simulation. A series of questions were then asked and the interviewee was invited to then respond. The interviews lasted approximately half an hour each.

Interview 1

Date: 26th August 2014

Name: Interviewee 1 – Architect

No.	Question	Response
1	With regards to the way things are at the present time within simulation what is it typically that simulation offers you as a practitioner?	We use it a lot throughout the projects that we engage in. A lot of the times we carry out simulation to predict how the building will behave. So you can have a good understanding of which systems can be applied to this building and how to build it in terms of configuration so it can give you answers about the optimum solution for the building under consideration. It's also useful for existing retrofit buildings as you can use simulation to see if a better solution can be found to reduce the energy consumption.
2	You mention energy consumption, are there any other parameters that you would want to extract?	Air temperature is another consideration that practitioners often need to understand and this is linked to thermal comfort of the occupant. Simulation must take on board elements like glazing, orientation of the building, different roof types. You may wish to specify different design temperatures for different areas and so you can try to design into the orientation more sunlight in the areas that require a higher air temperature using the suns heating capacity. You might also want to see from simulation the daylight entering a space and if the occupant needs to turn on lighting or not, or perhaps including solar light to minimise the energy use from lighting fixtures. So from building users the main aspects that simulation currently offers is energy consumption and CO_2 savings and temperatures for thermal comfort.
3	Do you think that simulation has developed as far as it can or is there room for improvement?	Yes there is room for improvement

4	What areas do you think would be useful for practitioners to examine and where do you see the future of simulation	Usually within simulation they are made for individual buildings without considering interactions with others. So community aspects is one area that building simulation should look to achieve better results. Even the shading that could be provided from other buildings could be better and also renewable energy systems. For example if you want to have a community that relies more on renewable energy systems you need to understand, not only the demand of one building but the combined demand of the community, and then simulate this to allow for renewable energy systems on a community wide scheme would be very useful. So things like demand side management, energy storage, smart grids, community connectivity, heat island effects are all issues that the user might wish to explore. In building simulation itself there is a lot of research going into behavioural models for occupants. Currently a lot of programs only take a static viewpoint of occupancy and does not vary the way this occurs in real life.
5	Would you agree that health and wellbeing within buildings is another area that is worth understanding more about?	I'm not really sure what simulation offers in that department but certainly it is something that should be addressed in terms of moisture content and indoor air quality, thermal, visual and acoustic comfort. These are all issues that are important to understand more about. The dispersal of pollutants is another area that deserves a lot more consideration.
6	What are the strengths that simulation offers in today's society?	It's useful to find a good design for one building, to find the right energy system that suits the building. Even if the demand is not quite accurate it will still find a good system for the buildings in question. Simulation in this respect provides a good approximation of the energy consumption and CO_2 emissions. But as far as the future of simulation goes it needs to be more accurate.
7	Do you see a future where practitioners wish to understand more about smart cities?	Yes I agree
8	Do you see a future where practitioners wish to understand more about demand side management systems and microgrids?	Yes if there is scope in this field it would be worthwhile understanding more about it.
9	Is health and wellbeing an important issue for simulation to address	Yes, this is one of the fundamental aspects designers should incorporate in building design.
10	Do you think that simulation could be more integrated?	Well it depends on what you want to use simulation for. If you want to improve a building you might require a lot of information e.g. if you have a model you may wish to assess different parts such as energy consumption and temperature profiles but then look at integration into smart cities and thermal and visual comfort and behavioural profiles of people. All of these are linked and so it would be useful to have a tool that could embody all of these systems into one.
11	So would you agree that having an integrated tool that could look at a complete building analysis on the effect of visual, thermal, acoustic, community connectivity and impacts as well as energy consumption and	As a designer simply by making one design decision there can be many different environmental effects and so it is imperative for the practitioner to assess the wide range of issues not just energy consumption but everything else as well. It is imperative that the next steps for building practitioners is to adopt a methodology of how to carry out these integrated views and extract all the relevant information that may be needed.

	heat island effects would be a useful thing?	
12	What about costs associated with the building	Currently there is not a lot available in building assessment of costs, but it would be useful to understand how certain design decisions can impact on the overall cost of a building. E.g. if the user specified an expensive type of glazing but could save money on the running costs of the building then this would be useful to display to clients. Currently simulation does not offer this flexibility. The development of BIM modelling has also allowed for the rise of information that can be contained within models. Within simulation it would be useful to take this material information and use it for calculating capital, running, maintenance and demolition costs associated with materials.
	.	It would also be useful for energy systems and to be able to calculate running, maintenance and demolition costs as some energy systems are quite pricey however could provide a lot of benefits over the lifecycle of a building.

Interview 2

Date: 26th August 2014

Name: Interviewee 2 – Engineer

No.	Question	Response
1	With regards to the way things are at the present time within simulation what is it typically that simulation offers you as a practitioner.	Well I think he point here is to size equipment when you design a building. The point is to size it and to know what the performance is and assess the economical and environmental analysis of the equipment. So Energy and Cost are key criteria here.
2	Are there any other parameters that you would want to extract?	Indoor Air Quality is another area that is crucial for health of the building occupants. I would be interesting to know how these values typically vary during the simulations. Air Temperature is also another factor that requires the attention of building practitioners and it's interesting to know how this varies over a simulation period.
3	Do you think that simulation has developed as far as it can or is there room for improvement?	There is always room for improvement
4	Would you agree that health and wellbeing within buildings is another area that is worth understanding more about.	This is the basic considerations that a practitioner must help to reach during building design to ensure that occupants are comfortable in the thermal, visual, acoustic and indoor air quality fields. The reasons the systems have been put in place is to achieve acceptable levels in all of these areas. For example something that can be difficult to know is the differences of temperature within a room for example different desk locations and one desk is receiving more draft than another this will affect room temperature which will affect thermal comfort. So point of reference is a big issue in simulation as well. I have seen a lot of bad designs because someone is situated under a cooling unit and is getting dumped with all the cool air.

5	What are the strengths that simulation offers in today's society	There's so many complexities in the way in which the building interacts with the environment and point of reference can be an issue
6	Do you see a future where practitioners wish to understand more about smart cities?	There are a lot of uncertainties which is causing a lot of oversizing in equipment. So you take the worst case scenario and you apply a factor of 1.5 or 2 because the practitioner is not sure if the results are accurate enough. So it would be useful to have simulation tools that are more accurate that would allow engineers to size plant equipment more accurately and less oversized. Within simulation there are a lot of engineering conversion factors and assumptions that are made and these really need to be more numerically accurate and realistic. For example thermal bridging could be better addressed and systems like green roofs could be better modelled and fewer assumptions made on them. Whilst it is important to understand these issues there must also be a balance between keeping the functionality of the tools simple and input parameters to a minimum as often this is time consuming and the practitioner will not want to spend a long time inputting various values.
7	Do you see a future where practitioners wish to understand more about demand side management systems and microgrids?	This is definitely as system that needs to be addressed and can be dealt better in control systems. There needs to be developed in the controls as you can have some demand profiles that depends on the users preferences or other external conditions as there can be a lot of energy generation from PV panel or wind and this should be taken into account in simulation and in tools. And I think for control systems it's almost impossible to take on board this type of scenarios. I think at the moment this demand supply management and community load sharing is out of the scope of building simulation but it would be useful to have in the future certainly.
8	Do you think that simulation could be more integrated?	It would be useful to have a tool that if you were to model a window you could then assess the heat losses in the winter, the heat gains in the summer, the glare within the room at any given point, the cost associated with installing the window and the energy savings that would be accrued over the years all of these issues would be useful to have. It is important though to keep the tools as simple as possible and user friendly. A lot of the time practitioners won't have the time or money to care about glare and so having the option to look at different areas is useful but not always necessary. Interoperability is also something that would be useful as in some instance you might use other specialist tools and having the ability to communicate between the two would be useful.
9	So would you agree that having an integrated tool that could look at a complete building analysis on the effect of visual, thermal, acoustic, community connectivity and impacts as well as energy consumption and heat island effects would be a useful thing?	As long as it's kept simple and flexible for the user would be useful. And the user does not have to put in a lot of input parameters. At some point maybe for a first analysis you don't care about where sensors are located for controls, or where the duct ends or the ventilation grille in the room you just want approximate figures. But then if the user wishes to go into more detail then these parameters can be inputted and the results assessed.

12	What about costs associated with the building	You might want to know equipment running maintenance demolition lifecycle. Costs are important for analysing any design. In some programs you have to define some cost parameters in order to get the cheapest or most cost effective option. But this is a problem if you don't want to know anything about the costs but you have to define cost parameters to receive your recommended output whether that is energy or temperature or anything. It would be very interesting having a cost analysis but it can be a problem if you need to define the cost parameters
14	Further Comments	Libraries should have complete databases for Heat Pumps Boilers, Walls everything that include parameters such as COP U-values and system efficiencies to minimise the input required by practitioners. Having BIM models that can be imported to the model and assign zones automatically.

Appendix B – Commercial vendor claims

The following list of claims were extracted from each vendor within the UK and compiled into the following table. These claims were taken from brochures, manuals and the respective websites of the vendors.

Table 12 Commercial vendor claims

Claim	Description	Claim	Description	Claim	Description	Claim	Description
1	Interoperability between software gbxml, idc, idf	21	Solar Shading Simulation	41	Measurement of velocity, temperature, pressure, density, humidity, chemical concentrations, local age of air, air change effectiveness possible at every single point in the entire domain	61	Mech Vent
2	Dynamic Thermal Modelling Capability	22	Daylight and Artificial Lighting Simulation	42	Daylighting - models lighting control systems and calculates savings in electric lighting	62	Solar Gain
3	Multiple Building Simulation	23	Building Load Calculations using ASHRAE Heat Balance Method	43	Visualisation of site layouts and solar shading	63	Gains from Lights, Occupants, Equipment
4	Integrative	24	Macroscopic Airflow (Bulk/Internal Zone) Simulation	44	Calculating heating and cooling equipment sizes	64	Control Set Point and Band, Optimum Start, Frost Protection
5	Indoor Air Quality Assessment	25	Dynamic Thermal Simulation	45	Heat transmission through building fabric including walls, roofs, infiltration, ventilation etc.		
6	Calculating Building Energy Consumption	26	HVAC equipment and control systems simulation - Design Load calculations for boilers, chillers fans pumps and heat recovery devices	46	Heating and Cooling Loads		
7	Condensation calculations can be performed on constructions	27	Right to Light of Buildings and Surroundings	47	CO2 generation		
8	Compare Low Carbon Technologies	28	Exterior wind effects, pedestrian comfort and pressure envelope	48	Heating and Cooling Plant Sizes		
9	Green Roofs, Thermal Storage including Phase Change Material's	29	Contaminant Dispersal	49	Required Plant Size, Plant radiant/convective characteristics		
10	Test Different Design Options	30	Indoor/Outdoor Thermal Comfort	50	Performance of Boilers and Heat Pumps		
11	Renewables Energy Systems e.g. Solar Thermal PV, Wind, CHP and Air Source Heat Pumps	31	and equipment heat gains, Direct and diffuse solar gains, interior and exterior conduction heat gains/losses,	51	Available Plant Capacities for heating and cooling		
12	Heat Island Effect	32	Energy - Annual end use and peak demand, running costs, carbon emissions. ASHRAE 90.1 Performance method.	52	Plant Schedules		
13	Pedestrian Comfort	33	Indoor Environment Quality	53	Thermal Insulation		
14	Evaluating Façade options for overheating and visual appearance	34	Room Ventilation rates and carbon dioxide levels	54	Thermal Capacity ("thermal mass")		
15	Draw Conclusions on Energy Use	35	Thermal Comfort incl. air, mean radiant, dry-resultant and surface temperatures, relative humidity, PPD, PMV,	55	Glazing Properties		
16	CO2 Emission's	36	Visual Comfort incl. daylight, views and glare	56	Built Form and Orientation		
17	Occupant Comfort	37	Sensible and Latent Load, Condensation Risk, Humidity, Resultant Temp, Mean Radiant Temp, Air temp, Energy Consumption	57	Climate		
18	Health	38	Useful for assessing;	58	Shading from Nearby Buildings and Self Shading		
19	Air Flow	39	Passive Design Components - Site, Orientation, Massing, Form, Layout, Glazed Areas, Glazing Types, Shading Devices, Thermal Mass, Insulation, Air Tightness, Daylighting and Natural Ventilation	59	Infiltration		
20	Thermal Simulation of naturally ventilated buildings	40	Active Systems - Interior and exterior lighting, process equipment, heating, cooling, ventilation, radiant heating and cooling, displacement ventilation, daylight dimming, green roofs, thermal storage	60	Nat. Vent		

Appendix C – Overall performance domains

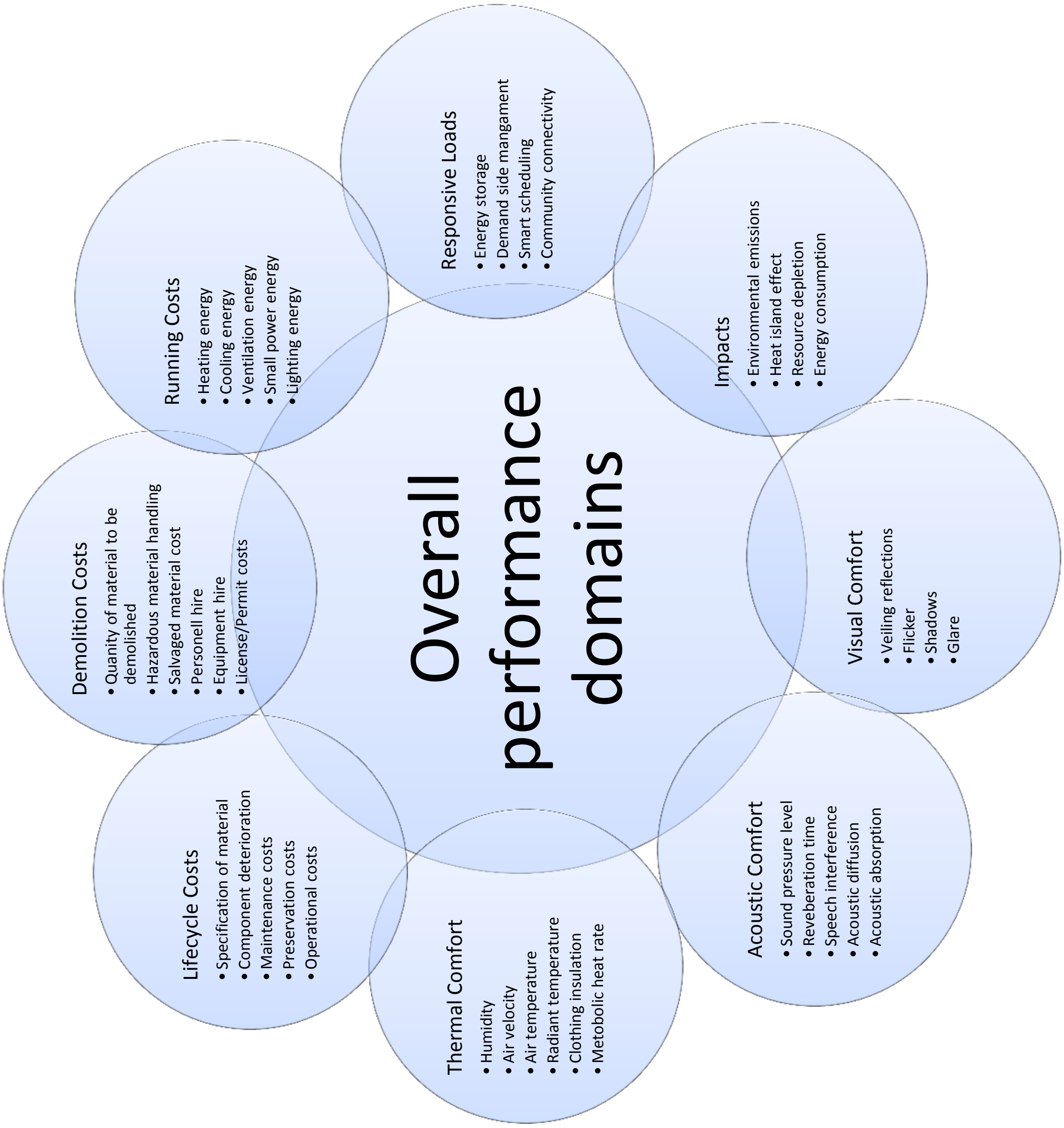

Figure27 Overall performance assessment domains

Appendix D – Overall performance criteria

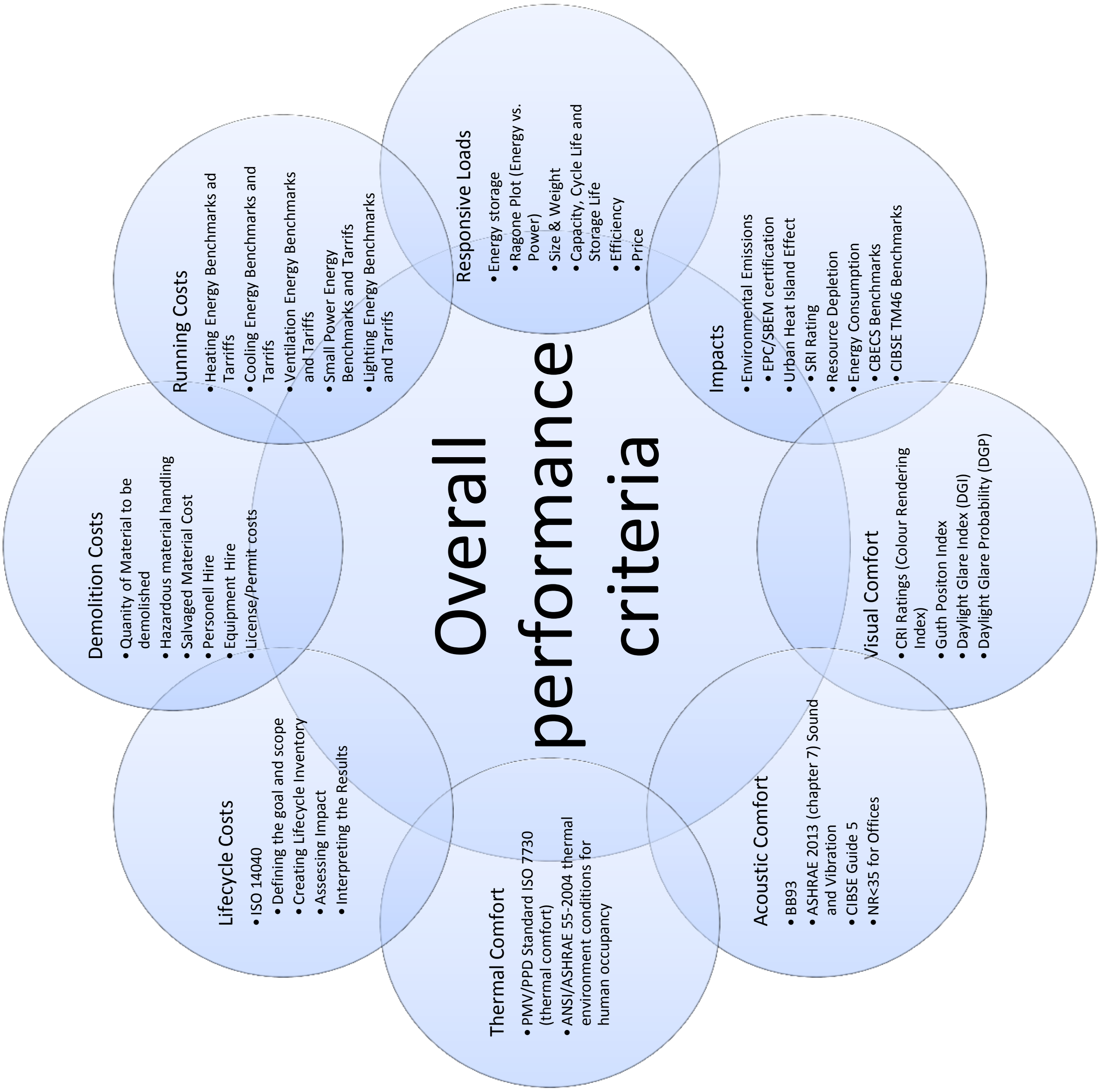

Figure 28 Overall performance assessment criteria