A Knowledge Management System to Optimise Comfort throughout the Building Life-Cycle

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Talk to Strangers

Abstract

Comfort is, in essence, satisfaction with the environment, and with respect to the indoor environment it is primarily satisfaction with the thermal conditions and air quality. Improving comfort has social, health and economic benefits, and is more financially significant than any other building cost. Despite this, comfort is not strictly managed throughout the building lifecycle. This is mainly due to the lack of an appropriate system to adequately manage comfort knowledge through the construction process into operation. Previous proposals to improve knowledge management have not been successfully adopted by the construction industry. To address this, the BabySteps approach was devised. BabySteps is an approach, proposed by this research, which states that for an innovation to be adopted into the industry it must be implementable through a number of small changes.

This research proposes that improving the management of comfort knowledge will improve comfort. ComMet is a new methodology proposed by this research that manages comfort knowledge. It enables comfort knowledge to be captured, stored and accessed throughout the building life-cycle and so allowing it to be re-used in future stages of the building project and in future projects. It does this using the following:

- Comfort Performances – These are simplified numerical representations of the comfort of the indoor environment. Comfort Performances quantify the comfort at each stage of the building life-cycle using standard comfort metrics;
- Comfort Ratings - These are a means of classifying the comfort conditions of the indoor environment according to an appropriate standard. Comfort Ratings are generated by comparing different Comfort Performances. Comfort Ratings provide additional information relating to the comfort conditions of the indoor environment, which is not readily determined from the individual Comfort Performances.

- Comfort History – This is a continuous descriptive record of the comfort throughout the project, with a focus on documenting the items and activities, proposed and implemented, which could potentially affect comfort. Each aspect of the Comfort History is linked to the relevant comfort entity it references.

These three components create a comprehensive record of the comfort throughout the building lifecycle. They are then stored and made available in a common format in a central location which allows them to be re-used ad infinitum.

The LCMS System was developed to implement the ComMet methodology. It uses current and emerging technologies to capture, store and allow easy access to comfort knowledge as specified by ComMet. LCMS is an IT system that is a combination of the following six components:

- Building Standards;
- Modelling & Simulation;
- Physical Measurement through the specially developed Egg-Whisk (Wireless Sensor) Network;
- Data Manipulation;
- Information Recording;
- Knowledge Storage and Access.

Results from a test case application of the LCMS system - an existing office room at a research facility - highlighted that while some aspects of comfort were being maintained, the building’s environment was not in compliance with the acceptable levels as stipulated by the relevant building standards. The implementation of ComMet, through LCMS, demonstrates how comfort, typically only considered during early design, can be measured and managed appropriately through systematic application of the methodology as means of ensuring a healthy internal environment in the building.

Dedication

To Elmer,

Since you were the better story teller in our duo, I'll let you do your dedication. Why break a successful tradition :-).

Advice

By Elmer Morrissey

"Prioritise a path that ensures you have enough Walter time in an environment that will support growth (spiritual/mental/whatever). Ultimately, what I'm advising is don't take an easy option that your gut rebels against. Back yourself and take charge. That may involve risks, or it may be an open door right where you are. But…, be careful how far you take rational thought, go with feeling without limits. Make whatever you want happen, don't force it or anything, just seek it. You'll know when you find it."

I miss you.

Acknowledgements

To the most important person in my life, Mam, thank you for all your encouragement, advice, chats, sacrifice, and nagging :-). You were, are, and always will be my hero.

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"If I have seen further it is by standing on the shoulders of giants." – Isaac Newton (mathematician & physicist)

Thank you all,
Walter.

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Acronyms

General Acronyms

BIM	Building Information Model(ing)
BLC	Building Lifecycle
CFD	Computational Fluid Dynamics
CSV	Comma Separated Value
EDM	Electronic Document Management
HVAC	Heating Ventilation and Air Conditioning
IAQ	Indoor Air Quality
IFC	Industry Foundation Classes
PIR	Passive Infrared
PMV	Predicted Mean Vote
PPD	Percentage People Dissatisfied
SME	Small-to-Medium Enterprise
WSN	Wireless Sensor Network

Comfort Performance Acronyms

CaCP	Calibrated Comfort Performance
CnCP	Construction Comfort Performance
CrCP	Control Comfort Performance
DCP	Design Comfort Performance
FCP	Future Comfort Performance
HCP	Historical Comfort Performance
ICP	Ideal Comfort Performance
OCP	Optimum Comfort Performance
RCP	Required Comfort Performance

Comfort Rating Acronyms

BAR	Benefit Analysis Rating
BSR	Building Success Rating
CR	Comfort Rating
CR-A	Comfort Rating - Actual

CR-C	Comfort Rating - Construction
CR-D	Comfort Rating – Design
CR-F	Comfort Rating – Future
CR-O	Comfort Rating – Optimum
CrSR	Control Success Rating
OER	Operation Error Rating
OSR	Operation Success Rating
PSR	Project Success Rating
PSR-A	Project Success Rating – Actual
PSR-P	Project Success Rating – Predicted
RCR	Required Success Rating

Contact Information

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Declaration

This thesis is my own work and has not been submitted for another degree, either at University College Cork or elsewhere.

Signed: Walter O'Grady

Walter O'Grady

Chapter 1

Introduction

1.1 Motivation

Evolution has conditioned human beings to optimise what is under their control in order to promote their survival, as natural selection rejects frivolous acts and wastage of time and energy [1], [2]. Human health and survival can be improved by improving living environments, and this has resulted in international climatic agreements [3] and the promotion of better living environments [4], energy efficiency [5], and building sustainability [6], [7].

Recently, developments to optimise living environments, and specifically the indoor environment, have shifted from an occupant perspective to an energy efficiency perspective.

1.2 Focus

This research focuses on improving the comfort of the indoor environment for occupants. In functional terms, the majority of indoor environments are designed for the purpose of supporting occupant activity e.g. houses and apartments for living, offices for working, etc. In financial terms occupants are usually the most significant element of a building. For example, in 2010, in Ireland the average cost to construct an office building was €3,300/m^2 [8] and the average office floor area per employee was 12m^2 [9]. This gives an average construction cost per employee of €39,600 over the entire life-time of the building, while the average employment cost per employee was €41,000 per year (not including office overheads) [10]. In developed countries, conditioning the indoor environment is typically only 1% of labour costs [11]. In fact, it was determined in 1989 that for the average business in the USA, salaries exceed the combined office costs of energy, maintenance, annualised construction and rental by a factor of 100. Therefore, a 1% increase in employee productivity would justify a doubling of the other costs

[12]. H.F. Levy, P.E. Professional Engineer & Life Member of ASHRAE, put it best when he said "*our real customer is the occupant, not the building.*"

1.3 Comfort

Comfort has been defined as *that condition of mind that expresses satisfaction with the environment* [13]. The environmental factors considered to affect occupants' satisfaction with the environment are thermal comfort, visual conditions, acoustic conditions, air quality, vibration, electromagnetic fields and electrostatic conditions [14]. In the absence of definitive scientific grading of the relative importance of these factors, there is a strong perception that thermal comfort and air quality are the most significant. Wyon, Fisk and Rautio [15] conducted a survey on the percentage importance of indoor environmental independent variables expected to affect occupant productivity across all industries. The results showed that the variables which affect thermal comfort and air quality accounted for 72% of the votes, variables affecting acoustics accounted for 12%, and variables affecting the visual conditions accounted for 7%. The remaining 9% was accounted for by two variables, personal control of the physical environment, which equalled 7%, and quality of cleaning, which equalled 2%. Variables that affect vibration, electromagnetic fields, and electrostatic conditions did not receive any grading in the survey, highlighting their perceived unimportance. It should be noted that, there can be individual industry bias with respect to these factors. An occupant survey conducted in hospitals showed that 'cleanliness and ease of maintenance' is regarded as the most important design factor [16], although this survey was not solely focused on productivity.

Given the relative importance of thermal comfort and air quality, these factors are the focus of this research and the term 'comfort' can be taken as a combination of thermal comfort and air quality. These two factors were chosen because within indoor environments they are strongly connected by the fact that they are both directly affected by the same heating, ventilation and air-conditioning systems (HVAC).

1.3.1 Thermal Comfort

For this research the thermal comfort is quantified in terms of the Predicted Percentage Dissatisfied (PPD) value, which is derived from the predicted mean vote (PMV) value specified by the CIBSE Design Guides [14]. The data used for the calculation consists of four environmental factors, which are:

- Air speed;
- Air temperature;
- Air humidity; and
- Radiant temperature.

And two personal factors, which are:

- Clothing level;
- And activity level.

A detailed definition of the PMV and PPD and how they are calculated is given in Annex C.

1.3.1.1 Factors that Affect Thermal Comfort

1.3.1.1.1 Temperature

The room air temperature and radiant temperature may be combined as the operative temperature. Temperature is usually the most important environmental variable affecting thermal comfort. A change of three degrees will change the response on the scale of subjective warmth, shown in Table C.1 in Annex C, by about one scale unit for sedentary persons. More active persons are less sensitive to changes in room temperature [14].

1.3.1.1.2 Air movement and draughts

The cooling effect of air movement is well known. If this cooling is not desired, it can give rise to complaints of draught. It should also be noted that people are more tolerant of air movement if the direction of the air movement varies. However, it has been shown that dissatisfaction due to draught is not only a function of mean air speed and local air temperature, but also of fluctuations of air speed [14].

1.3.1.1.3 Humidity

Humidity has little effect on feelings of warmth unless the skin is damp with sweat. Thus, for most practical purposes, the influence of humidity on warmth in moderate thermal environments is low and humidity in the range 40–70 % RH is generally acceptable [14].

1.3.1.1.4 Clothing

Clothing worn by people indoors is modified by the season and outdoor weather, as well as by the indoor thermal environment. The wearing or otherwise of an article of clothing is equivalent in its effect on subjective feelings of warmth to raising or lowering the operative temperature. The clothing insulation provided by an individual garment consists of the effective resistance of the material from which the garment is made plus the thermal resistance of the air layer trapped between the clothing and the skin. Other factors, e.g. looseness of fit, also affect the insulation value. The value of clothing insulation of an ensemble, if estimated from design standards is not precise, but will usually be within 20%. For sedentary occupants, the insulating properties of the chair will also affect thermal comfort [14].

1.3.1.1.5 Metabolic heat production

Metabolic heat production is largely dependent on activity. Building standards give metabolic rates for specific activities. Care must be used when applying these due to uncertainties in measuring metabolic rates and in defining the tasks. It is reasonably accurate (i.e. ± 20%) for engineering purposes for well-defined activities with a low metabolic rate. However, for poorly defined activities with a high metabolic rate the error may be as high as ± 50% [14].

1.3.1.2 The Adaptive Aspect of Thermal Comfort

Part of the contemporary research into thermal comfort uses an adaptive method. The adaptive method is a behavioural approach, and rests on the observation that people in daily life are not passive in relation to their environment, but tend to make themselves comfortable, given time and opportunity. They do this by making adjustments, or adaptations, to their clothing, activity and posture, as well as to their thermal environment.

People tend to become well-adapted to thermal environments they are used to, and find them comfortable. These thermal environments are within the range customary for the particular type of accommodation, according to climate, season and cultural context [14].

These customary temperatures are subject to gradual drift in response to changes in both outdoor and indoor temperature, and are modified by climate and social custom. A gradual change, over several days, in indoor temperature would not cause discomfort, provided it was in line with the other parameters, specifically the outdoor temperature. This is because the change would be compensated by a corresponding change in clothing [17], or other adjustable variables.

The extent of seasonal variation in indoor temperature that is consistent with comfort depends on the extent to which the occupants can adjust their clothing. Occupant clothing level has been found to change based on external temperature, particularly in free-running buildings in temperate climates [17], [18]. As a result the temperature that people find comfortable indoors also changes [18]-[20]. Adaptive theory suggests that people respond on the basis of their thermal experience, with more recent experience being more important. A running mean of outdoor temperatures, weighted according to their distance in the past, is therefore the most appropriate.

The adaptive approach suggests that the comfort temperature for a free running building varies greater with outdoor temperature than that of a heated or cooled building. Occupant adaptation is assisted by the provision of personal control over their individual thermal environment. This control can be in the form of fans, openable windows, or local heating control [14].

There are insufficient data available to sufficiently analyse domestic dwellings for adaptive thermal comfort. It has been suggested that people are less sensitive to temperature changes in their own home than at work, and in general people have more adaptive opportunity at home [21].

The adaption method and the PPD method for thermal comfort prediction are complimentary. Improvements in occupant comfort could be achieved by combining the two methods. A local comfort measurement system is required to enable this combination. The adaption method incorporates the occupants' ability to control their environment to determine the comfort temperature, such as opening a window, which would have an effect on some of the PPD factors. Therefore to include these changes into the PPD calculation an appropriate real-time measurement system is required. Also the adaptive method predicts the occupants' ability to adapt to seasonally changing outdoor temperatures, and so indirectly predicts clothing level. Combining clothing prediction with the PMV method would also be beneficial.

1.3.2 Air Quality

Human sensitivity to pollutants can be categorises as either odours, irritants, or both. For comfort, indoor air quality may be said to be acceptable if not more than:

- 50% of the occupants can detect any odour, and
- 20% experience discomfort, and
- 10% suffer from mucosal irritation, and
- 5% experience annoyance, for less than 2% of the time [14].

Currently the comfort implications of pollutants are not the primary considerations of Building Standards Organisations in setting occupational exposure limits. Sensory comfort guidelines are only available for a small number of substances [22]. The more serious health impacts of pollutants found in buildings are naturally more prominent. Some of these, e.g. radon, are odourless and do not affect comfort but may have serious effects on the health of any individuals exposed to them. The most significant compounds in indoor air with respect to overall health impacts are probably carbon monoxide, house dust mites, pet allergens, moulds, formaldehyde, nitrogen dioxide (and other oxides of nitrogen), and possibly particles. While the significance of particulate matter in ambient air is undisputed, there is an unresolved question about the relative toxicities of vehicle derived and other airborne particles, such as may be generated by cooking and heating appliances inside buildings. Carbon dioxide at low concentrations is typically used as a marker for indoor air quality and for ventilation requirements, reflecting the pollutant loading from exhalation by the occupants. The maximum concentration is 5,000 ppm in working conditions [23] and it can be an asphyxiant at extremely high concentrations. The role of volatile organic compounds in causing ill health is somewhat disputed, although the measurement of total volatile organic compounds has in the past been used as a general marker for indoor air quality, and volatile organic compounds have been implicated both in 'sick building syndrome' and so-called multiple chemical sensitivity.

Some of the main challenges to maintaining appropriate indoor air quality are:

- Monitoring the pollutant levels in operational buildings
- Monitoring the pollutant levels in the outdoor air. Because, as a result of urban pollution, outdoor air can no longer be automatically considered as a clean air source. The most important pollutants in outdoor air are generally considered to be airborne particles (e.g. PM10, PM2.5), ozone, nitrogen dioxide, carbon monoxide and sulphur dioxide.
- Buildings, and their components, produce pollutants and so buildings themselves can be a constant source of their own pollution.

Apart from some exceptions, including legionella bacteria, radon gas, and lead and benzene from motor vehicle exhaust emissions, the airborne contaminants likely to be encountered in non-industrial buildings do not usually result in irreversible health effects. Also these serious indoor air pollutants are not guaranteed to exist is all indoor areas [14]. Therefore, in building areas where bio-effluents from occupants are the most significant pollution, using the CO_2 level as an indicator of air quality is the most appropriate [13], and so for this research the air quality is measured in terms of the CO_2 level.

1.4 The Economics of the Indoor Environment

1.4.1 General

Improving the comfort of the indoor environment has proven health and productivity benefits, and therefore, financial benefits. A comprehensive study was carried out of worker self-evaluation of productivity with relation to, personal factors such as motivation and health, environmental factors such as temperature and lighting, architectural factors such as office layout and decoration, and job factors such as stress and control [24]. This found that the principal factors, which affect self-assessed productivity, were:

- An overall unsatisfactory office environment;
- A crowded workspace;
- Job dissatisfaction.

The relationship is defined by the following equation:

$$P = 6.8510 - 0.3625*En - 0.1542*JD - 0.1329*CS \qquad (1.1)$$

Where:

- P is the self-assessed productivity;
- En is an overall unsatisfactory indoor environment;
- JD is the job dissatisfaction;
- CS is crowded working space.

This shows that the indoor environment had the greatest impact on self-assessed productivity.

The study found that the two principal complaints about the indoor environment were thermal problems, which are controlled by thermal comfort, and sick building syndrome symptoms, which are controlled by IAQ. As previously stated in §1.3, a combination of thermal comfort and IAQ is the definition of comfort for this research. When the above information is combined with another survey of approximately 7,000 people, which showed that 25% of absenteeism in the Netherlands is due to the indoor environment [25], the significance of comfort with relation to absenteeism becomes apparent.

1.4.2 Thermal Comfort

As previously shown, a significant aspect of the indoor environment is thermal comfort. Occupant thermal comfort in the indoor working environment directly affects worker productivity [11], [26]. Thermal discomfort also causes stress. Stress related absenteeism in the UK increased by 107% between 1996 and 2001 [14]. An increase in the PPD of 10%, above its minimum value of 5%, can be caused by modest changes in the environmental parameters as shown in Table 1.1. However, it can be calculated that a change in PPD from 5% to 15% results in a performance reduction of 5% [25]-[27]. Taking again an average employee in Ireland with a cost to the employer of €41,000, these modest environmental changes now equate to a €2,050 loss. Considering the energy costs per employee are a mere €90 per annum, as shown in Table 1.2, it is easy to see the relative importance of maintaining optimum comfort.

Table 1.1 – Values for Contributing Environmental Parameters for a PPD of 5% and 15%

	Value	**Change**	**Value**
Predicted Percentage Dissatisfied (%)	**5**	**+10**	**15**
Contributing Environmental Parameters			
• Air temperature (°C)	22	**-1.5**	20.5
• Radiant Temperature (°C)	22	**-1.5**	20.5
• Humidity (%)	50	**-15**	35
• Air Speed (m/s)	0.1	**+0.1**	0.2
• Clothing Level (clo)	0.9	**0**	0.9
• Activity Level (met)	0.9	**0**	1.2

Table 1.2 – Energy Cost per Person for an Average Office Building in Great Britain (used in the absence of a suitable Irish value)

Costs	
Office Floor Area per Person (m^2) [9]	12
Energy Cost per m^2 (€) [28]	7.50
Total cost (€)	**90**

1.4.3 Air Quality

Indoor air quality (IAQ) is a significant factor affecting the indoor environment. The quality of occupant health is proportional to the quality of the indoor air, that is, the better the IAQ the fewer sick building syndrome symptoms such as asthma and allergies are present in building occupants [11]. In 2005 the World Health Organisation stated that indoor air pollution was responsible for 1.6 million deaths worldwide each year. That is one every twenty seconds [29]. It was estimated in 1997 that respiratory infection cases and sick building syndrome was costing the USA up to $43 billion in health costs and lost productivity each year [30]. The World Health Organisation constitution states that *"Health is a state of complete physical, mental and social well being, not merely the absence of disease and infirmity*" [31]. Therefore, the indoor environment should also be managed in such a way as to promote health, not merely to avoid illness [14]. Indoor air quality directly affects employee performance. It has been shown that upgrading an office from a non-low-polluting building to a low-polluting building can result in a 6.5% increase in productivity [32]. A low-polluting building is defined as a building with a sensory pollution load of 0.1olf/m^2, whereas a non-low-polluting building is one with a sensory pollution load of 0.2olf/m^2 floor area or higher [13], where 1olf is the sensory load on the air from an average sedentary adult in thermal neutrality. This 6.5% increase in productivity would equate to an average benefit to an Irish employer of €2,665 per employee. The productivity benefits resulting from improving indoor air quality can be up to 60 times higher than the associated increased costs [33].

1.5 Current Situation

1.5.1 The Construction Industry

Currently, the majority of indoor environments are designed, constructed and operated by the construction industry. Therefore, in order to achieve the social and financial benefits of improved environmental comfort the construction industry needs to be improved. The construction industry is quite unique in relation to other industries. It is difficult to draw comparisons between it and other industries such as the automotive and aerospace industries or try to identify how it can emulate the efficient processes of those highly automated industries [34]. It's uniqueness comes from the fact that it is a fragmented industry [35], [36]. It contains many different disciplines and companies, which come together for short term, once-off projects [37]. While this causes problems [38], it also shows the flexibility and adaptability of the industry, which can produce very permanent structures from a very temporary process. Improving a temporary, non-repetitive process, as one unit is an immense task. However, as previously stated, this temporary process is comprised of numerous smaller elements, such as professions, companies, systems, software etc. These elements are re-used repeatedly throughout the industry [39]. Therefore, by improving each element individually, the process as a whole can be improved incrementally.

The quality of the products produced by the industry depends greatly on the quality of information used. Much of the same information is required throughout the life of the project, by different companies in different disciplines with different systems. Rebolj states that it is an overlap like this that can provide the best opportunities for innovation [40]. Methods of information utilisation are numerous and ever-changing (new businesses, systems and software; existing ones evolving; old ones discontinuing) but the information used remains constant (temperature will always be temperature, humidity always humidity, and so on). Therefore, improving the management of information is one such incremental improvement, which can provide consistent benefits continuously into the future.

1.5.2 Industry Inefficiencies

At present, the management of information is poor, mainly because of poor integration of the three stages of the building lifecycle (BLC). The process flow for an indoor environment project is a series of three stand-alone sub-projects - design, construction and operation - which have little interconnection in terms of personnel, systems or data. They are only linked by output documents containing limited data. Therefore, there is a huge loss of information at each stage of the process through a combination of personnel changeover and poor data exchange. The current information flow through the construction stages is shown in Table 1.3.

Table 1.3 – Current Information Flow [41]

	Information Management											
	Design				**Construction**				**Operation**			
	R	C	S	O	R	C	S	O	R	C	S	O
Information Description												
Design												
Concept		●	●	◖	◖		◖		◖		◖	
Design Intent		●	●	◖	◖		◖		◖		◖	
Design Calculations		●	●									
Simulation Models		●	●									
Simulation Output		●	●									
Design Alternatives		●										
Construction Specifications		●	●	●	●		●					
Operation Specifications		●	●	●	●		●					
Construction												
Revised Construction Specifications						●	●	◖	◖		◖	
Revised Operation Specifications						●	●	◖	◖		◖	
Maintenance Requirements						●	●	◖	◖		◖	
Commissioning Data						●	●	◖	◖		◖	
Operation												
Revised Operation Specifications										●	◖	
Operational History										●	◖	
Maintenance History										●	◖	

R = Received
C = Created
S = Stored
O = Outputted
◖ = Partial Transfer
● = Full Transfer

For design, this means that data on the operation of previous, perhaps similar, projects is rarely available to the designers. Potentially, such data could be used to calibrate simulation models to make them more accurate for future designs [42]. Computational fluid dynamics (CFD) can be used for detailed indoor environment design. However, CFD is under-utilised in the building sector partially due to a lack of consistent information across the building lifecycle, including a lack of a formalised instrumentation framework that can measure the effectiveness of the CFD design model by measuring the actual operation. This results in un-calibrated CFD models producing little more than 'pretty pictures'. These are graphics of un-validated CFD models, which are used to explain complex HVAC solutions, desirable thermal environments, and airflow patterns in buildings. Enabling building specific CFD models to be calibrated will help make CFD an effective tool for building design and operation. Developing these, more accurate, models and other models that can simulate peoples' comfort, well-being, and productivity under realistic, dynamic working conditions would be beneficial [25] as they can be used as:

- Virtual prototypes, allowing designers to virtually analyse the effects of proposed changes to the indoor environment that the model is created for;
- Benchmarks for fault detection systems [43];
- The base model for designing similar indoor environments in the future e.g. a geometrically equal space in a different location; and
- As a source of inputs for software assisted CFD model generation for buildings [44].

If we genuinely want to guarantee optimal comfort levels within buildings, and consequently a more productive workforce, we need to use operational data to provide a building-specific operation database, which would allow designers to develop more building-specific solutions. This information would also compliment the generalised design standards that are now used. However, currently, designers must rely on un-calibrated design models [45] based on generalised design standards to produce designs.

It has been shown that benefits could be achieved from updating the design standards [11], [26] but currently the main source of information to do this comes from expensive, intermittent, experimental case studies. These laboratory experiments are also not as reliable as real world experiments when dealing with productivity [26]. A building-specific operation information model would be a valuable source of information to aid the improvement of design standards.

The relationship between indoor environment and comfort makes it possible to design on the basis of comfort improvement. The experimentally proven productivity benefits of improved comfort make it financially beneficial. However, optimisation of comfort is not considered as a project goal when designing the indoor environment [25], [26], instead designing for the maintenance of minimum comfort levels is acceptable. This is mainly because, unlike energy, where the majority of buildings have at a minimum the bulk energy use recorded and made available by the energy provider, comfort is rarely recorded. This makes it difficult to determine the relative success of design decisions in relation to comfort and in turn makes it difficult to use comfort as a design parameter.

During the entire project, but more prominently during construction, poor information transfer causes unnecessary expense [46] which can be up to 30% of costs in some projects [47]. This expense arises from increases in the likelihood of delays to forecasted time-lines and cost overruns due to unforeseen events [40] and the increased probability of defective work [48]. Information is predominantly document based with documents being either physically or electronically transferred between two or more project members. Due to the imprecise nature of the information exchange, errors easily occur and are compounded by further exchanges. This means the original information and its ownership are not easily accessible or identifiable. It is a data chain with each link being a project member, similar, it could be said, to the children's game Chinese Whispers and with comparable results. An example is illustrated in Figure 1.1.

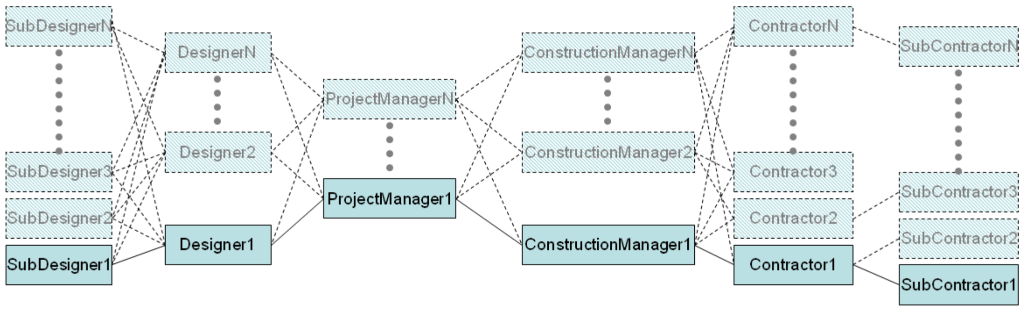

Figure 1.1 – Information Flow during Construction

The commonly cited hindrances to information transfer, as listed by Chassiakos and Sakellaropoulos [38], are:

- Transfer methods are time consuming and expensive - Although the internet and mobile communication have actually made transferring information cheap and almost instantaneous, locating the information and/or the member who has it, is still time consuming and expensive;
- Geographic distance between project members - Like any other business, geographic distance will always be an issue for construction projects as the most effective method of information exchange is, indisputably, face-to-face communication [49], although it is not always the most economical method;
- The variation in project members' specialties - Transferring data between disciplines causes problems because disciplines tend to store data in their own particular data format and information is often lost in the translation; and
- The volume and dissimilarity of information involved in a construction project - The volume is not so much the problem as having to transfer this volume of information. Transferring large quantities of information often causes delays and errors and so is best avoided.

Baron William Thomson Kelvin (physicist, mathematician and engineer) once stated "*…when you cannot measure it… your knowledge is of a meagre and unsatisfactory kind*". This theory can certainly be applied to indoor environments. The operation of indoor environments is based on knowledge and its constituent components information and data. The current process however may not grant the operator with sufficient access to information on:

- The comfort conditions within the environment;
- The HVAC systems servicing these environments; and
- The design intent associated with the environment.

Consequently there is insufficient information available to obtain useful results from the many methods available to analyse building operation [43], [50], [51]. In fact, a system to record actual comfort in operational buildings is almost non-existent [52]. Existing environment monitoring systems usually only measure air temperature to monitor thermal conditions. This is insufficient as temperature does not necessarily reflect comfort. High or low temperatures relative to the current design temperature could still be comfortable given other appropriate thermal parameters. Likewise the correct design temperature does not necessarily guarantee comfort due to other unfavourable thermal parameters such as radiant temperature or high air speeds. Basically air temperature is currently used as the de-facto overly simplified measure of comfort.

When it comes to dealing with an under-performing environment not only does the operator not have sufficient information to get a good understanding of the problem, but also if they do decide to make changes to the servicing HVAC system they will usually have to reverse-engineer it to discover what conditions it was designed to produce. This is because, for many reasons, there is usually not adequate environment sensors installed [45] and often the information on installed systems is incoherent, incomplete, inadequate and sometimes incorrect. Building simulation models which could be used to improve operation [45], [50] either do not exist or are no longer available. Efforts have been made to improve the access to this information by making the initial project manager responsible for its collection and coordination [53] but this is merely moving responsibility '*from post to pillar*'.

1.5.3 Summary

§1.5.2 highlights the following inefficiencies. It should be noted that some of the following points are evident throughout the entire project but are included in the most relevant sub-project here.

1.5.3.1 Design

The lack of operational information available to designers during design often means:

- The success, or otherwise, of their designs in different situations (times of the year, etc.) are hard to track;
- Designs fail to make significant advances from the experience of previous projects;
- The data to calibrate design models is not available;
- Design flaws can carry over into consecutive projects;
- Design models are not re-used for future developments to the project;
- Since comfort is not measured during operation, it is difficult to effectively use comfort as a design parameter;
- General prescriptive standards are relied on instead of building-specific information; and
- There is little information, other than expensive case study results, available to progress, expand and improve existing prescriptive best-practice standards and benchmarks.

1.5.3.2 Construction

The poor transfer of information in construction means there often is/are:

- Time wasted locating information and information owners;
- Uninformed decisions made due to the lack of adequate information;
- Project delays due to inadequate item and change tracking;
- Delays caused by the untimely delivery of information;
- A compromise of information integrity because:
    - Manually transferring information is error prone;
    - Transferring large quantities of information runs a high risk of it not transferring completely;
    - There are more steps than required in the information-flow process which increases the probability of errors;
- Translation errors when transferring information between disciplines;
- Project delays caused by transferring large quantities of information;
- Issues using bulky paper documents on-site;

- Information duplication which is wasteful in terms of time and cost; and
- Issues ensuring the most current information version is used.

1.5.3.3 Operation

The information is not easily accessible during operation which often means:

- Uninformed decisions are made about the building operation;
- The design intent for the environment is not easily determinable;
- System flaws are difficult to identify;
- Comfort is difficult to track and improve;
- Analysis of the data on the actual, required and designed environments is difficult; and
- The successful application of performance-based assessment is hindered.

1.6 Previous Proposed Information Systems

Improving the current construction system by integrating the design, construction and operation stages would eliminate numerous inefficiencies and there has been no shortage of effort invested in attempts to do this. Proving this are groups and projects such as ATLAS [39], BLIS [54], buildingSMART [55] , COMBI [56], COMBINE [57], COMMIT [34], CONCUR [58], CONDOR [59], CORENET [60], CoVES [61], Divercity [62], ECTP-PICT [63], HITOS [47], I3-Con [64], ICAtect-II [65], ICON [35], IFC mBomb [66], IFC Model Server [67], inpro [68], ManuBuild [36], OSCON [69], OSMOS [37], RATAS [70], ROADCON [71], SPACE [72], Strat-CON [73], Wisper [74], WIMSCI [38]. These projects are described further in Annex B. Some of these are old, starting over quarter of a century ago [70], and some are new, and currently ongoing [63]. Some are small scale, with only a few individuals [38], and some are big, with budgets in the millions of euro and many international members [55]. Analysing these varying systems, methodologies and technologies identifies one clear point. They all agree that the industry would benefit from adopting a more on-line data-centric collaborative approach with information modelling as the modern method of choice.

Generally, construction lags behind other industries in the adoption of ICT, [36] despite the productivity growth that it enables [68]. Computer applications have changed most aspects of engineering to varying degrees, with data communication being one of the least affected [75], which is still document based. To-date limited use has been made of data collaboration in construction with electronic document management (EDM) making the only real progress. There are many EDM systems available and some are specific to construction such as: Constructware[1], BIW:Collaboration[2], FusionLive[3], Buzzsaw[1], e-Builder[4], eRoom[5], IronSpire[6], Meridian[7], Primavera[8], ProjectCenter[9], Project Collaborator[10], ProjectWise[11], TeamFlow[12]. EDMs are used more extensively in other industries. However the IT Barometer showed that between 2000 and 2003, 23-25% of construction sector companies in Singapore, Denmark and Sweden used EDMs [60]. EDMs provide basic collaborative tools [73] but are limited as they provide little, if any, file editing options [59]. EDM does not have the collaboration potential of information modelling, because it does not store information in a consistent manner and instead stores information in various document formats. Therefore, EDMs are not intended to achieve the benefits of information modelling as they are designed to manage documents not data. Still, they are a significant step along the collaborative path and toward building information modelling (BIM) [76].

BIM is the process of providing a single, logical, consistent source for all information associated with a building. To date, the use of BIM systems has had limited diffusion into the industry with only a few pilot projects worth noting:

- The Singapore planning e-submission system, CORENET [60];

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[1] usa.autodesk.com
[2] www.biwtech.com
[3] www.sword-ctspace.com
[4] www.e-builder.net
[5] www.eroom.net
[6] www.ironspire.com
[7] www.meridiansystems.com
[8] www.oracle.com/us/primavera
[9] www.bricsnet.com
[10] www.computerguidance.com
[11] www.bentley.com
[12] www.teamflow.com

- BART's and London Hospital project used AutoDesk's ADT[1];
- The Eureka Tower in Melbourne used Graphisoft's ArchiCAD[13];
- The Sydney Opera House Renovation project used Bentley[11]; and
- The Freedom Tower in New York is using AutoDesk's Revit[1] [77].

These examples do highlight an interesting question. Even though research on data collaboration has been around for decades [70], and even though the current BIM technology is technologically viable, economically feasible, and user desirable and, therefore, satisfies the criteria for innovation sense [73], why then are the only usable BIM solutions just derivatives of existing commercial software packages? Why has the aforementioned research not been adopted in the industry in any significant way?

1.7 Why are we still here?

The aforementioned previous proposed systems have come from some of the most accomplished research groups in the field. The systems are comprehensive and advanced, integrating various differing construction components into one complete system. The fact that the industry is generally unchanged from its document based roots demonstrates that these systems have been unsuccessfully implemented into the industry.

It is common knowledge that:

- The construction industry is reluctant to change [38], [78];
- The construction industry is slow to innovate [36];
- Generally, new proposals are hard to implement [39], [79]; and
- Organisations like to stick to their traditional methods while only partially adopting new systems [57].

It is not common knowledge *why* the construction industry is reluctant to change. Or more accurately, it is not *commonly asked*, why the construction industry is reluctant to change.

Everett M. Rogers identified five criteria for the diffusion of innovation that must all be met in order for an innovation to be successfully adopted into an industry. These are relative advantage, complexity, compatibility, trial-ability,

[13] www.graphisoft.com

and observe-ability [49]. The following is an analysis of the previous proposed systems under these headings.

1.7.1 Relative Advantage

In industry, advantage, like everything else, is measured in money, and new proposals will only be adopted if they are profitable [38], [60]. To date, the changes required to adopt the proposals have been too large and, therefore, too expensive for the industry to adopt [38], [80]. In 2005, while the construction sector was the largest employment sector in the EU, 96% of the sector's 2.3 million enterprises employed less than 20 people [73], and these small-to-medium enterprises (SMEs) simply cannot afford the investment and continuous-upgrade costs of large IT systems [60].

1.7.2 Complexity

In comparison to current systems BIM technology is complex. Sufficient data encapsulation [56] and appropriate representation of reality [76] are cited as reasons for this but ultimately it is mainly because it is new and different to the current system. However, requiring large changes to the current system compounds these issues [81] and deters its adoption [38].

1.7.3 Compatibility

The previous proposals have required a complete new system to be adopted instead of the current [34], [35], [57], [68], [71], [72] as it is believed BIM technology is not compatible with the current system [37], [46], [60], [62], [76]. Some believe that the BIM technology is not developed enough [81] and that there are too many unsolved issues that would conflict with the current project process. Some of these issues are:

- Object Orientated Databases can have duplicate and inconsistent data [76];
- Data ownership [75], [76], [82];
- Change management [46], [56]; and
- Data backup [38].

1.7.4 Trial-ability

The majority of the industry cannot afford to try the BIM technology as the only reasonable solutions are large comprehensive systems from commercial vendors. These require large changes (eg: cultural, systemic, technical, etc.) and, therefore, large expense. There are little or no commercial BIM 'light' systems.

1.7.5 Observe-ability

Users need to see the benefits and marketing of BIMs has been poor [81]. Case-studies are a good way to show potential [56], [83], [84] and there has been some progress made here, such as the government led Danish 'Digital Construction' project [78], and the other examples mentioned in previous sections. However these were not enough to overcome the lack of compliance with the other four of Rogers' criteria.

1.8 GiantSteps or BabySteps?

Once analysed using Rogers' criteria, the reason for non-adoption becomes clear. Essentially most of the previous proposals required too large a change for them to be successfully adopted by the SME dominated industry. A large change or an 'all-or-nothing' approach generally hinders progression [81]. To achieve the BIM's full potential a large change is ultimately required but this can be achieved through a number of smaller steps or 'BabySteps'. Improvement on an incremental basis is more favourable for implementation, as is proven by commercial software vendors [46]. Some research groups have also started to adopt this incremental approach for innovation [59], [60], [67], [73].

The BabySteps approach proposed by this research states that for an innovation to be adopted into the industry it must be implementable through a number of small changes. The following is a discussion of the benefits of BabySteps, again under the headings for the diffusion of innovation.

1.8.1 Relative Advantage

Taking smaller steps is more economical from two perspectives. Firstly, from a technical perspective:

- Providing a demand for smaller, more specialised applications could open up the market to more application developers, which could improve competition;
- The development of smaller component based systems allows for:
    - Scalability: allowing users to start with a small investment;
    - Flexibility: enabling users to adapt new systems to their existing ones and so minimise costs by not having to replace their existing systems;
- Smaller applications can run on cheaper hardware and are cheaper to install, run and maintain [34].

And secondly, from a user perspective, users adapt to small changes easier and need less costly training, especially if existing technology is used [34], [35], [78]. Since employees are the key resource [40], [62], [82] catering for them could also reap financial benefits in productivity.

1.8.2 Complexity

Smaller specialised tools are naturally simpler. This makes them easier to use, maintain [65] and extend to accommodate future requirements.

1.8.3 Compatibility

Smaller component based systems are usually more compatible with existing systems as they allow for:

- Integration by accommodating and complimenting existing systems [40], [75], [80];
- The closer tracking of user needs by increasing communication between academia, commercial software producers, and the industry. This connection is important for implementation [62] as, Flyvberg states a poor one "*can lead to ritual blind alleys, where the effect and usefulness of research becomes unclear and untested*" [83], and can also cause frustration in academia over the lack of adoption of new proposals. Research results can only be deployed industry wide if all parties are able and willing to apply the new methods [68];
- Flexibility, enabling users to customise systems to their own particular needs [34], [68];

- Extendibility to accommodate future requirements;
- The mirroring of existing results [85]. That is the production of the same results as the current system in a more efficient manner.

Therefore proposed improvements do not have to solve all the current system problems. The best of both new and old systems can progress and the entire system can evolve.

1.8.4 Trial-ability

Small changes make it easier to perform trials in businesses. This is because it is easier to:

- Get employees' involvement [78];
- Change human and organisational culture [59];
- And move away from reliable traditional methods and habits.

As Mark Twain said “*Habit is habit and not to be flung out of the window by any man, but coaxed downstairs a step at a time.*” Humans, and the systems under their control, evolve and rarely suddenly change. Users adapt to small changes easier and need less training, especially if existing technology is used [35], [78].

1.8.5 Observe-ability

Small changes make it easier to carry out product demonstrations and pilot projects. Demonstrating the system, even in a small limited scale, can be enough to show its potential. Here too, a close connection between academia, commercial software producers, and the industry is beneficial, as it is through this connection that the potential of new proposals can be conveyed from academia to the industry.

1.8.6 Example

In most cases, when the Diffusion of Innovation Criteria is applied to a low budget market, such as the construction industry, it can be simplified to the BabySteps approach. The adoption of the mobile phone is an example that can be used to clarify this point. Table 1.4 analyses the main aspects of the mobile phone under the Diffusion of Innovation Criteria approach and under the BabySteps approach. The analysis identifies if the mobile phone aspect passes or fails the requirements of the approaches.

When first released the mobile phone did not satisfy the BabySteps approach. It was too expensive to be adopted into low budget markets, such as the personal use market. In recent years when the financial change required was reduced, which also satisfied the BabySeps approach, it got more widespread adoption.

Table 1.4 – Analysis of the Mobile Phone under the Diffusion of Innovation Criteria approach and under the BabySteps approach

Mobile Phone Aspect	Diffusion of Innovation Criteria	BabySteps
It connects with the existing phone system.	**Pass**. It satisfies the Compatibility requirement.	**Pass**. A Small change is required to incorporate it.
It operates like an existing phone.	**Pass**. It satisfies the Complexity requirement.	**Pass**. A Small change is required to learn how to use it.
It is used in public.	**Pass**. It satisfies the Observe-ability requirement.	**Pass**. No change is required to see its benefits.
It is easy to borrow and try.	**Pass**. It satisfies the Trialability requirement.	**Pass**. A Small change is required to try it.
It saves approximately two working hours a week: **- and when first released, in 1983, cost $3,000 (plus running costs).**	**Pass**. It satisfied the Relative Advantage requirement. In high budget markets, such as corporate financial industry, the value of two hours of work a week equalled or exceeded $3,000 (plus running costs) distributed over the phones lifetime.	**Fail**. A big financial change was required for low budget markets to adopt it.
This table continues on the next page.		

Mobile Phone Aspect	Diffusion of Innovation Criteria	BabySteps
This table starts on the previous page.		
- and currently can cost $50 (plus running costs).	**Pass**. It satisfies the Relative Advantage requirement. The value of two hours of work a week usually equals or exceeds $50 (plus running costs) distributed over the phone's lifetime.	**Pass**. A small financial change is required to adopt it.

1.9 Summary

Improving the comfort of the indoor environment improves the health and productivity of the occupants thereby realising significant social and economic benefits. To improve comfort the fragmented construction industry needs to be improved. This can be done by improving the management of comfort information throughout the building life-cycle by increasing the current integration of the industry and reducing the information fragmentation. There is plenty of research promoting information modelling to improve the integration of the construction industry. However, this has not yet been significantly adopted by industry. This research deduces that this is because the current proposals are too large making them undesirable. Therefore, to get a new system adopted, an incremental approach, using a number of small changes or BabySteps, is proposed.

In order to achieve the economic benefit of improved comfort the construction industry must be improved. So far, it does not seem capable of achieving this because the quality of information used is inadequate.

Chapter 2

Room for Improvement

2.1 Introduction

"Every day you may make progress. Every step may be fruitful. Yet there will stretch out before you an ever-lengthening, ever-ascending, ever-improving path. You know you will never get to the end of the journey. But this, so far from discouraging, only adds to the joy and glory of the climb" – Winston Churchill (politician). Indoor environments work. And the current system for providing them works. But there is always room for improvement. The Japanese have developed a philosophy around this theory known as Kaizen [86]. It focuses on continuous improvement of a process and is regarded as a major contributor to the success of the Japanese economy since World War II.

2.2 Problem Definition

So what improvement can be made to the comfort of the indoor environment? James Baldwin (author) stated that, *"If you know whence you came, there are absolutely no limitations to where you can go"*. Therefore, to identify an improvement, a concise definition of the current situation is first required. From the previous chapter the main inefficiency identified is that there is a lack of comfort knowledge management throughout the building lifecycle (BLC) and this adversely affects occupant comfort.

Firstly, this is because the existing knowledge on comfort is managed in a way that makes it unavailable and unusable for future use. For example, as previously stated, operation data is not available to the Designer to produce calibrated simulation models, which can be used to improve future designs.

Secondly, the comfort history is also unavailable. In this research the comfort history is defined as the continuous descriptive record of the comfort throughout the project, with a focus on documenting the items and activities, proposed and implemented, which could potentially affect comfort. For example, the reason for choosing a particular heating system during the design stage is usually not available at the operation stage and this knowledge can become very useful, and in some cases necessary, if alterations are planned for the environment that the heating system serves.

And thirdly, from a diffusion of innovation point of view, most of the previous attempts to improve the information management were not successfully adopted. It is deduced that this is because they did not comply with a suitable implementation approach such as BabySteps.

2.3 Hypothesis

Ralph Waldo Emerson (essayist, lecturer, and poet) once wrote, "*As to methods there may be a million and then some, but principles are few. The man who grasps principles can successfully select his own methods. The man who tries methods, ignoring principles, is sure to have trouble.*" The principle to be learned from the problem definition, described in §2.2, is:

> *Improving the management of comfort knowledge can improve comfort.*

The following hypothesis was derived from this principle:

> *The occupant comfort in the indoor environment can be improved if the comfort knowledge gained at each stage of a building project is captured, stored and made available to future project stages and future projects in a consistent and unambiguous manner.*

2.4 Improvements

The improvement proposed by this research is to improve the management of comfort knowledge and this will enhance the occupant comfort of the indoor environment. This will be achieved by capturing, storing and making available all comfort knowledge as it is created. This means that this knowledge can then be re-used in future stages of the project and in future projects.

Improving the exchange and re-use of knowledge during the project can integrate the project stages more meaningfully. It can improve designs by allowing design success to be measured because information on how the actual environment is operating will be available in an explicit, structured format. Making all information accessible from a single storage format and location can reduce information transfer errors and expense. It can also improve operation by allowing the building operator to access information on the design intent of the indoor environment. This research can result in indoor environments being operated closer to their design intent and significant advances in future designs and redesigns due to feedback from the operation of previous designs to designers. §2.4.1 to §2.4.3 give a list of the main improvements proposed by this research separated into their relevant project stage. These improvements can be correlated with the inefficiencies listed in §1.5.3. They identify how, in theory, improving comfort management would address each of those inefficiencies. It should be noted that some of the following points are evident throughout the entire project but are included in the most relevant stage here.

2.4.1 Design

Providing easy access to a source of ever increasing knowledge on the comfort of the operational indoor environment can enable:

- The success of previous designs to be measured and quantified allowing designs to progress and advance in a consistent manner;
- An improvement in the accuracy of simulation models because operational data is available to calibrate them;
- The prevention of reoccurring flaws as the feedback on the operation will improve design flaw detection;
- The storage and re-use of simulation models for future project stages and projects;
- Comfort to become a significant design parameter because it will be measured throughout the BLC;
- An increase in building specific knowledge which complements and improves the existing general design standards;
- The identification of more appropriate measurement locations within the indoor environment. This will lead to an infinite progression where these better measurement locations will provide better measurement

data, which will enable the development of better design models, which again will lead to better measurements, and so on; and
- Improved use and development of tools to support comfort design.

2.4.2 Construction & Commissioning

Storing information on the indoor environment in a single location and providing easy access to it for all can allow:

- Relevant personnel to have immediate and constant access to all information once it is inputted;
- The construction to be carried out closer to the design intent because the design information is more accessible and explicit;
- For more accurate tracking of changes made during construction as notes on any alterations made can be stored directly into the same storage format and location;
- For a reduction of information duplication, transfer time, errors and therefore project delays, since information will only need to be stored once and not continuously transferred between people; and
- Relevant personnel to have access to the most current information.

2.4.3 Operation

Easy access to the design, construction and detailed operation information simultaneously can allow:

- More informed decisions to be made on the building operation;
- Operation of environments closer to design intent and, therefore, attain the designed comfort level;
- Comfort to be quantified, analysed and improved during operation;
- Easier identification of system flaws;
- The development of comfort performance based assessment similar to the BREEAM assessment method for energy [7];
- The development of occupant driven environment management. That is, adjusting the environmental conditions to suit the number and location of occupants. This is similar to how current passive infrared (PIR) sensor based lighting systems work; and

- Improved use and development of tools to support comfort management.

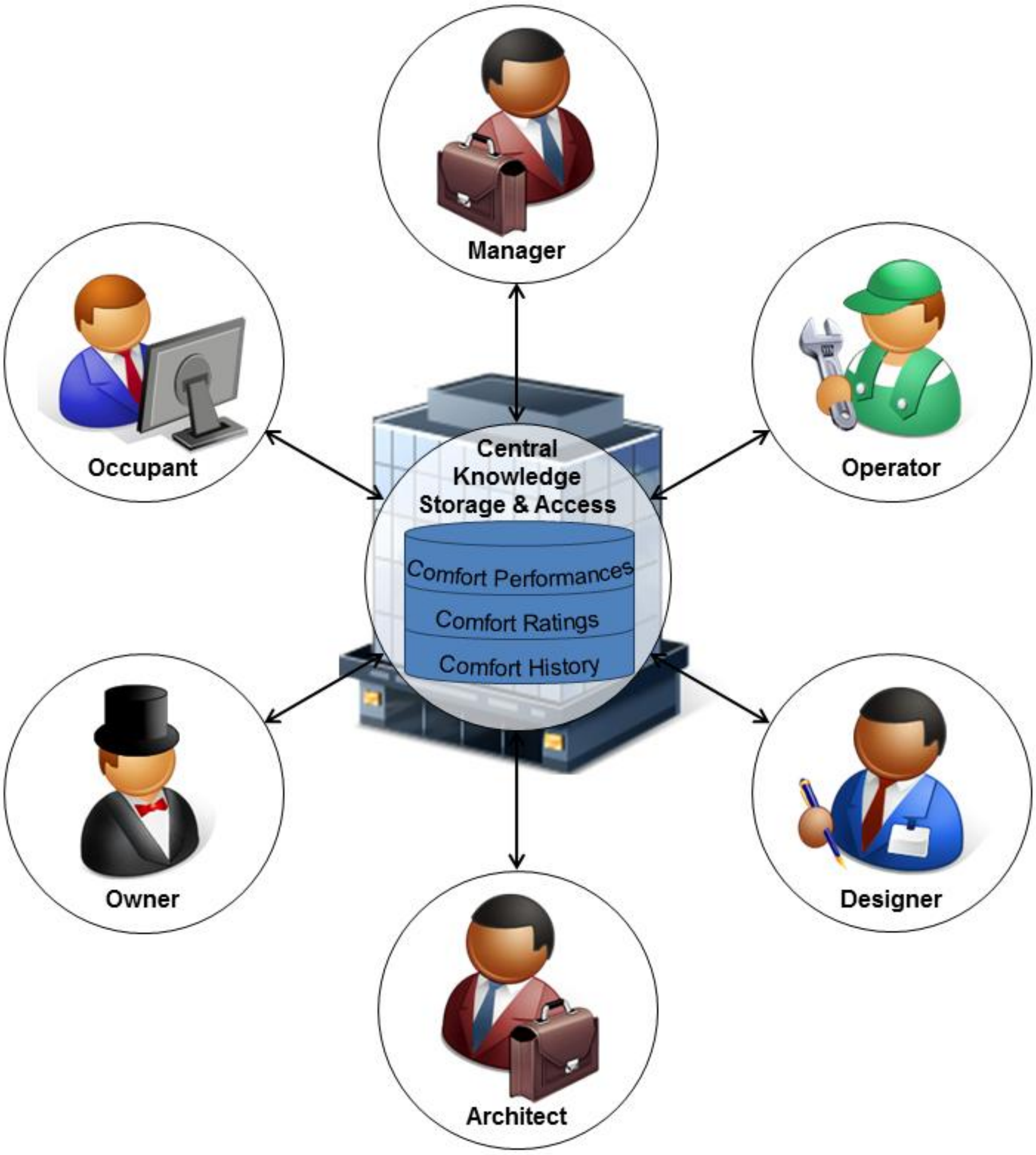

Figure 2.1 – Improving data transfer by reducing data transfer

2.5 Research Question

The main question that needs to be answered to prove this hypothesis is:

- How can comfort knowledge management be improved?

Chapter 3 answers this question. It describes a methodology that facilitates knowledge management through the BLC by enabling knowledge gained at each stage of a project to be available to future project stages and future projects. In order to answer the main research question Chapter 3 also answers the following important sub-questions:

- What is knowledge?
- How do you define comfort at each stage of the BLC?
- What information is available from these definitions?
- What other knowledge is available? and
- What are the storage and access requirements for this knowledge?

Chapter 3

The ComMet Methodology

3.1 Overview

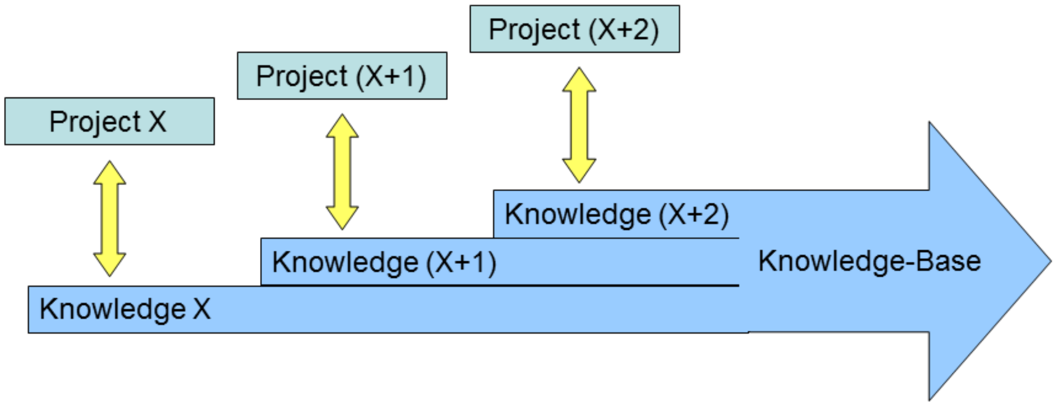

Figure 3.1 – Knowledge Re-Use

A methodology can be defined as *a set or system of methods, principles, and rules for regulating a given discipline*. In this case the discipline is the re-use of comfort knowledge and the following chapter describes the methods, principles and rules proposed to regulate it.

To improve knowledge re-use, a new methodology to manage comfort knowledge through the BLC was developed. The comfort methodology, named ComMet, enables knowledge gained at each stage of a project to be available to future project stages and future projects as shown in Figure 3.1. ComMet specifies that all knowledge must be captured, stored and made available in a consistent and unambiguous manner. §3.2 describes how this knowledge is defined and captured. §3.3 describes how it is stored and made available in a consistent and unambiguous manner.

ComMet is a core methodology. It can provide the basis and support necessary for other systems. It does this by regulating the knowledge that is required to improve comfort. This knowledge can be used in an infinite number of scenarios with different users, graphical interfaces, etc. Some sample scenarios are described in this chapter but these are relatively unimportant. The knowledge is what is important not the systems that use it as they cannot exist without the knowledge being provided by ComMet.

ComMet is analogous to an industry. In the same way as an industry captures raw material and processes it into useable products with many applications, ComMet captures the raw comfort knowledge and processes it into a useable form with many applications in future project stages and future projects. The knowledge is made available to whoever wants it and how they want to use it. A use is usually found for good quality knowledge once it is made available in an accessible format.

ComMet brings together many emerging technologies in areas such as measurement, calibration, optimisation and control. As with most technologies on the leading edge of research they are still immature and have weaknesses. However, to paraphrase Kimon Onuma (CEO of Onuma Inc.) if you wait for the perfect time you will never make progress. So with this in mind ComMet is designed to work with these technologies in their current state but will also work even better when these technologies inevitably improve in the future. ComMet and these technologies are mutually beneficial to each other because these technologies require information from various stages of the project to operate and improve, which ComMet can provide, and ComMet requires information from them to operate and improve. More detail on this will be given in the following sections.

3.2 Knowledge

3.2.1 What is Knowledge?

Knowledge is '*the acquaintance with facts, truths, or principles, as from study or investigation'*. Its relationship with data and information can be expressed as: information is data with meaning, and knowledge is information with context. For example: '20' is a piece of data; '20°C' is a piece of information because the '°C' gives the data meaning; and 'The room temperature is 20°C' is a piece of knowledge because the 'room temperature' gives the information context. It could be said that information is now *known* about the 'room temperature' and this is knowledge.

Comfort knowledge can then be defined as *the acquaintance with facts, truths, or principles, as from study or investigation, in relation to comfort*. Essentially, comfort knowledge is all knowledge during the project that is relative to comfort.

Knowledge is what is important [35], [82], [87] and it needs to be re-used more [36], [39], [47], [48], [73], [85], [88]. Improving the re-use of comfort knowledge can enable occupant comfort and, consequently, occupant health to be improved. In fact, occupant health can be improved directly by simply increasing the occupant's knowledge of their environment as it improves their ability to understand and control it [89].

3.2.2 Comfort Knowledge Sources

This comfort knowledge will be obtained from the following three sources:

- Comfort Performances – These are simplified numerical representations of the comfort of the indoor environment. Comfort Performances quantify the comfort at each stage of the building life-cycle using standard comfort metrics;
- Comfort Ratings - These are a means of classifying the comfort conditions of the indoor environment according to a suitable standard. Comfort Ratings are generated by comparing different Comfort Performances. Comfort Ratings provide additional information relating to the comfort conditions of the indoor environment, which is not readily determined from the individual Comfort Performances.
- Comfort History – This is a continuous descriptive record of the comfort throughout the project, with a focus on documenting the items and activities, proposed and implemented, which could potentially affect comfort. Each aspect of the Comfort History is linked to the relevant comfort entity it references.

Figure 3.2 shows a simplified schematic of where the Comfort Performances, Comfort Ratings and Comfort History occur during the project. §3.2.3 to §3.2.7 discuss these three knowledge sources in more detail.

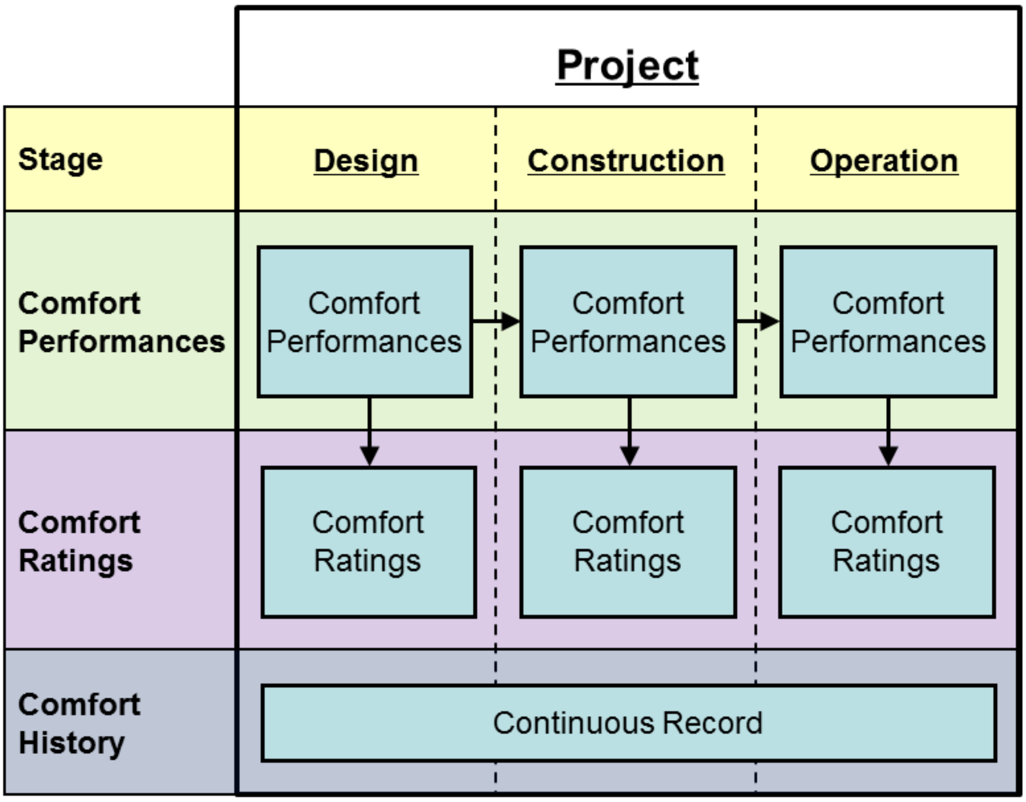

Figure 3.2 – Comfort Performances, Comfort Ratings and Comfort History

3.2.2.1 Comfort Knowledge Use Scenarios

3.2.2.1.1 Scenario – Actual Comfort Rating

Figure 3.3 depicts a typical scenario of how one aspect of the Comfort Knowledge could be used and this section is a high-level description of this scenario. More details on the elements mentioned here are contained in the following sections.

One of the Comfort Ratings developed for ComMet is the Comfort Rating – Actual (CR-A) and it will be used as an example for this scenario. It is generated from the Actual Comfort Performance and the Ideal Comfort Performance. It classifies the comfort which exists in the actual operational environment and can have a value of A – E. There are many stakeholders in a building project and typically five of them have an interest in the CR-A and, as specified by ComMet, they also will have access to it because it is stored in the accessible Knowledge-Base. In fact current technologies allow the stakeholders to be automatically informed of the status of the CR-A should they require it. The five stakeholders are the building's Owner, Occupant, Manager, Operator and Designer.

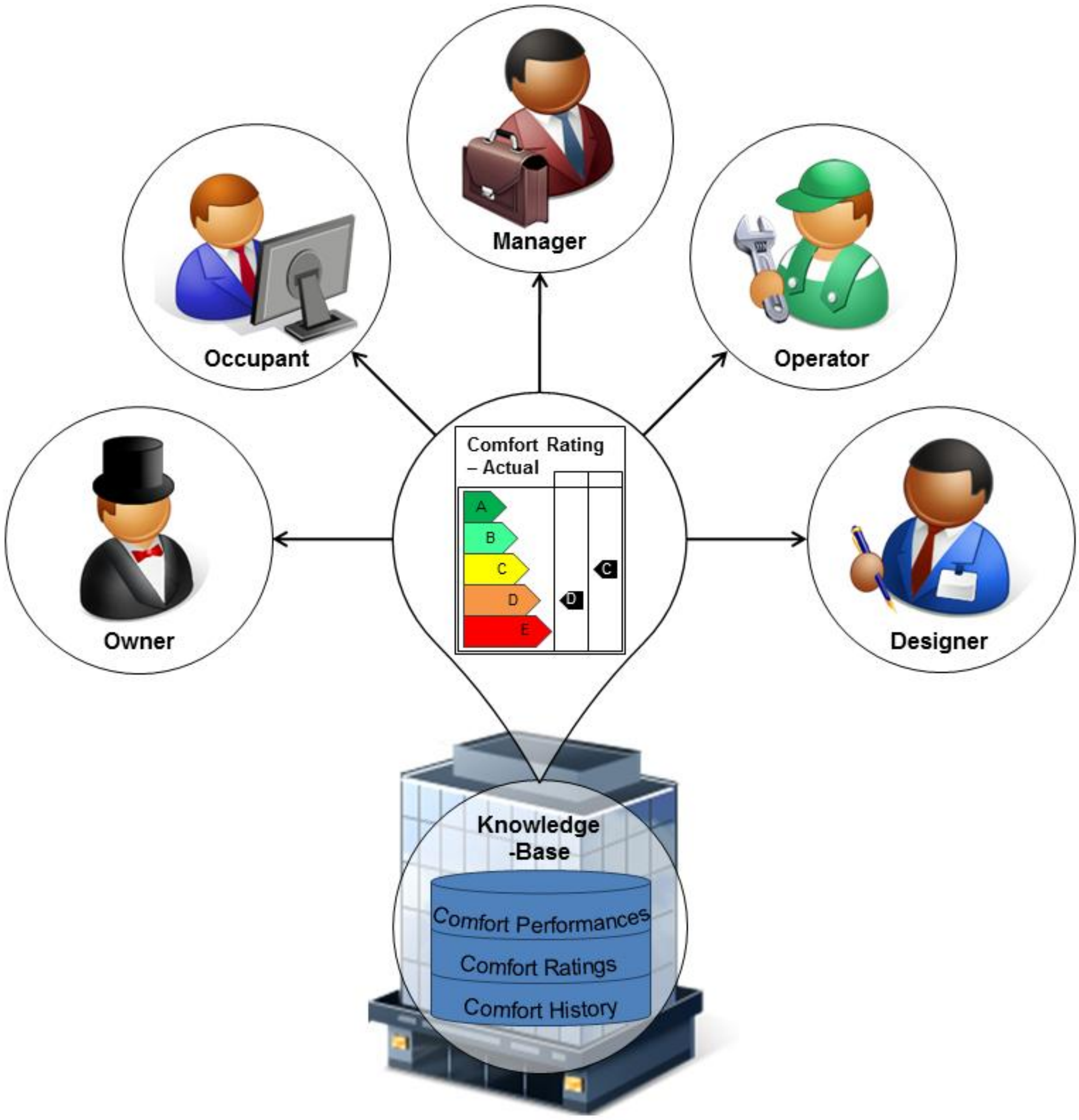

Figure 3.3 – ACR Use Scenario

Given a situation where the value of the CR-A drops to an unacceptable level the following scenario could result. Firstly the Owner will be concerned because the reduction in comfort will result in a reduction in productivity of the occupants which in turn results in a loss of revenue. This is a great improvement for the Owner because usually they have no idea what the comfort is like in the building and so could be making losses due to reduced productivity unbeknownst to them.

The occupant will be concerned because the CR-A is a direct measure of their comfort and naturally they will not want to work in an uncomfortable environment. This improves the situation for the Occupant because currently if the occupant is feeling uncomfortable they might not understand why they feel that way. There are many reasons for discomfort such as environment, clothing, illness, tiredness, etc. The CR-A informs the Occupant about the comfort of the environment and so allows them to make a more informed decision about their comfort.

The building's Manager will want to deal with the unacceptable CR-A value because if it is not rectified in an appropriate time then both the Owner and Occupant will probably issue complaints. This improves the Manager's current situation in many ways. Usually the Manager has to deal with an operational issue and a dissatisfied occupant because there is no automatic notification of the issue. And if they received a complaint about discomfort they cannot reliably check if the environment is at fault. Also the Manager cannot usually classify the level of comfort when communicating the issue to the Operator. For example enabling the Manager to state that the CR-A in a room has a value of 'D' is much more useful than them having to state that the occupant in a room is 'uncomfortable'. Current building monitoring systems can provide the Manager with information on the environmental conditions in a room, such as air temperature and CO_2, but, reasonably, environmental physics, such as how these conditions affect comfort, is outside the Manager's expertise.

The Operator is naturally concerned about the CR-A value as it is their job to maintain the comfort conditions in the environment at an appropriate level. Also if it is not rectified the Manager will probably request that the issue be dealt with. In order to address the issue the Operator will check to see if the operation strategy is implemented properly and that there are no faults in the HVAC system. If that is the case then they will request an updated operation strategy from the Designer. This process is an improvement on the current situation for the Operator because usually they only know there is an operational problem either if the Manager informs them of the discomfort of the occupants or if the building monitoring system reports an error. Neither of these accurately quantifies the comfort. Firstly the occupant perception of comfort, while valid, is subjective. Secondly current building monitoring systems usually only measure air temperature and, in the rare case, CO_2 and, as previously stated, air temperature is an unreliable indicator of comfort, but it is what current building operators usually have to work with. Also the Operator is a HVAC systems expert. They implement the operation strategy as created by the Designer. Usually however, if there is an operational strategy issue, it is up to the Operator to devise an ad-hoc speculative solution. This is because no method is in place to easily allow the Designer to provide their expertise.

The Designer will access the Knowledge-Base, review the conditions in the environment and will design an updated control strategy that will improve the comfort conditions. The Operator can then implement this strategy. A situation where this event could occur is if there are extreme weather conditions such as a very low external temperature, which would affect the internal temperature and in turn the internal comfort. The existing operation strategy might not have been designed for these temperatures and so an updated strategy would be required. Usually the Designer has no involvement in the operation of the building. ComMet provides a method to include the Designers expertise in the building operation specifically by enabling an interaction between the Operator and Designer with the purpose of improving the operation strategy continuously so the Comfort Rating - Actual is maintained at a level that optimises comfort and productivity.

In this scenario ComMet allows stakeholders to communicate comfort. It achieves this by converting comfort into the quantifiable entity that is the Comfort Rating - Actual which can have a value of A – E.

3.2.3 Comfort Performances

3.2.3.1 General

Performance can be defined as *quality of functioning*. In this case it is the quality to which the indoor environment functions at providing occupant comfort. The Comfort Performances quantify the level of quality. These performances are created at each stage of the BLC, which enables the comfort to be quantified as the project progresses through the stages. These performances define the comfort levels at a specified location and, as previously stated in §1.3, the definition of comfort for this research is given by a PPD value and a CO_2 value. However, since the definition of comfort is constantly being refined this methodology is independent of the comfort definition used. ComMet is designed to be flexible enough to use any definition of comfort that is currently the most appropriate. It can facilitate various definitions of comfort, such as, the future inclusion of acoustics and lighting as comfort parameters. There are typically ten Comfort Performances in a project and the sequence in which they are created during a project is shown in the Figure 3.4. For clarity, the performances are divided into project stages and whether the data used to generate it was from a building standard, simulation, or measurement.

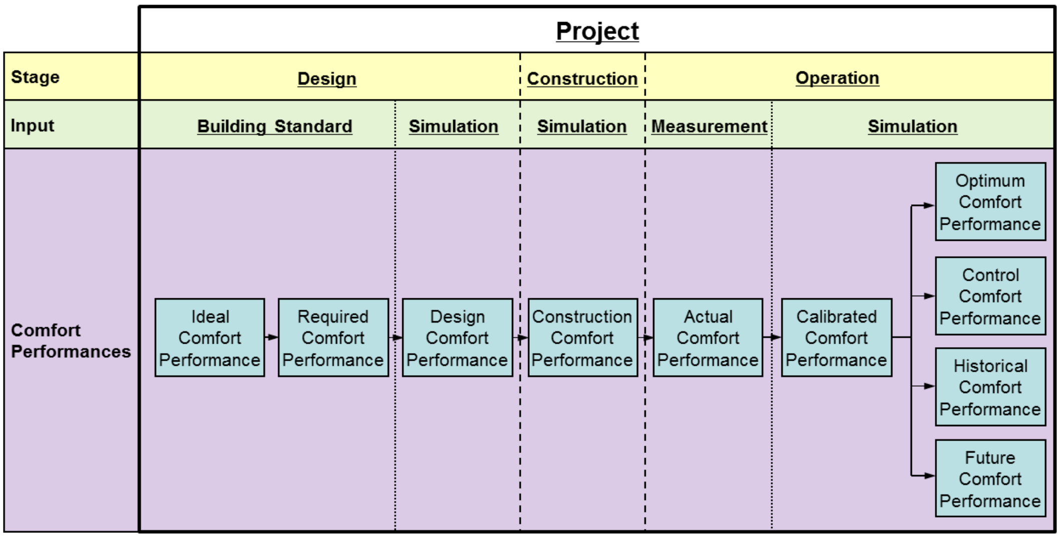

Figure 3.4 – Comfort Performance Creation Sequence

Since the construction sequence can vary depending on the project the methodology can facilitate the exclusion of performances from the sequence or the inclusion of new different performance types. It should be noted that the exclusion of the Actual Comfort Performance results in the proceeding performances being unreliable. This is explained in more detail in §3.2.3.7.

There can be numerous versions of the Comfort Performances also. For example, there can be many design options and so many Design Comfort Performances. Usually design alternatives are discarded once the design option is finalised, but storing these versions of the Design Comfort Performance is a source of knowledge, which can be re-used. If a particular design option generates an inadequate Comfort Performance then that design option will be excluded from the current project and if captured and stored it can be excluded from future projects too without requiring a new Comfort Performance of that design option being generated each time.

The general creation process for the Comfort Performances is shown in Figure 3.5. The required data is inputted into the appropriate creation tool or tools, which then generates the Comfort Performance.

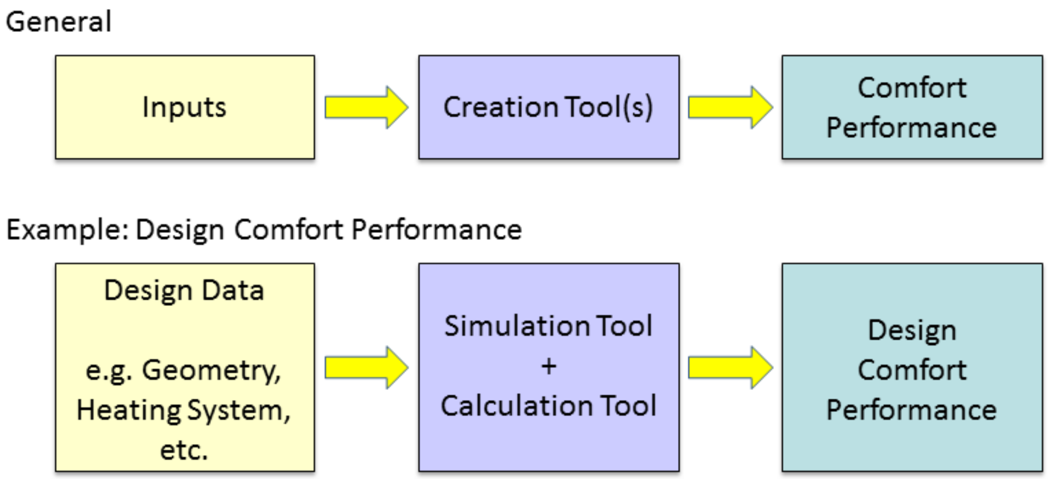

Figure 3.5 – Comfort Performance Creation Process

In order to maintain consistent information storage, the Comfort Performances generated at each stage are of the same format irrespective of the source of the inputs or the tool used to create them. This allows for one-to-one comparisons between Comfort Performances. The Comfort Performance is a set containing a PPD value and a CO_2 value and for this research is written as (PPD%,CO_2ppm). The reason that it is a set of values is because it is not practicable to formulate a single index that quantifies the individual's response to these environmental factors, and there may be additive or synergistic effects resulting from interactions among them [14]. The set format allows the inclusion of other parameters in the future, such as acoustics and lighting, as the comfort definition develops.

3.2.3.2 The Comfort Model

The Comfort Model is a simulated model of the indoor environment. It is used to generate the simulated Comfort Performances, as shown in Figure 3.6.

ComMet does not require a particular modelling technique, but the technique must be able to model all the physical parameters of the indoor environment necessary to calculate the comfort parameters specified in §1.3 and the boundary conditions that affect these parameters. Computational fluid dynamics (CFD) is one suitable modelling technique. It can model the physical components of the indoor environment, such as walls, furniture, people, and air, to produce the required environmental values to calculate the PPD value and CO_2, which are necessary to calculate comfort. CFD is explained in more detail in §4.3.2.2. The final comfort calculation is carried out using a calculation tool such as a spreadsheet. The values of the environmental parameters, from the Comfort Model, are used as inputs in the thermal comfort equations to generate the PPD value using the calculation tool. The thermal comfort equations are explained in Annex C. This PPD value is then combined with the CO_2 value, from the Comfort Model, to form the Comfort Performance.

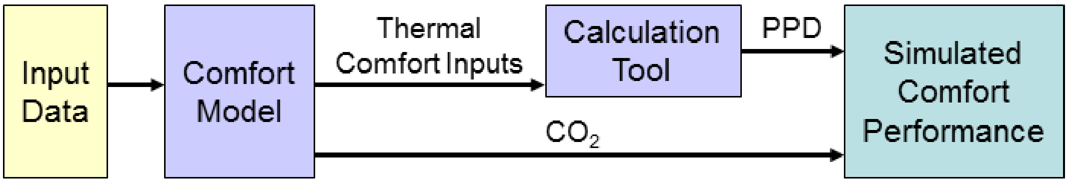

Figure 3.6 - Comfort Performance Creation using the Comfort Model

As the building project progresses the model's boundary conditions are changed to match the conditions of the environment at the current project stage. The Comfort Model can then be used to produce the values of the environmental parameters needed for the comfort calculation. For example, at the design stage the design data is used in the Comfort Model to produce the values of the environmental parameters needed to generate the Design Comfort Performance.

As with other building simulation models, the most appropriate data is to be used. This data has many sources, such as measurements, building standards, and best practice documents.

§3.2.3.3 to §3.2.3.12 describe in detail each of the Comfort Performances that were identified in Figure 3.4.

3.2.3.3 Ideal Comfort Performance (ICP)

The ICP quantifies the ideal or best possible comfort levels that can be achieved. The inputs for the ICP come from building standards and for the

CIBSE guides the ICP is (5%,750ppm). No creation tool is required for the ICP as it is based on the prescriptive building standard, and is essentially a prescribed Comfort Performance.

3.2.3.4 Required Comfort Performance (RCP)

The RCP quantifies the minimum or legally required comfort levels to be achieved. The inputs for the RCP again come from the building standards, and for the CIBSE guides the RCP for an office space is (13.4%,1,200ppm). The RCP can be different depending on the type of space. For example, corridors, offices, and canteens would have different RCP’s as the legal required comfort in these spaces differs from each other. Like the ICP, this is a prescribed Comfort Performance.

3.2.3.5 Design Comfort Performance (DCP)

The DCP quantifies the expected comfort levels based on the design data. The DCP is generated from the Comfort Model. Using the relevant design data, the model computes the design environmental values. These environmental values are inputted into the calculation tool that creates the Comfort Performance. The relevant design data would usually consist of location geometry, heat sources, pollutant sources, etc.

3.2.3.6 Construction Comfort Performance (CnCP)

The CnCP quantifies the expected comfort levels based on the construction data. As with the DCP, the CnCP is generated from the Comfort Model using the relevant construction data. The relevant construction data would usually consist of location geometry, heat sources, pollutant sources, etc.

This performance may or may not differ from the DCP depending on whether the input data differs due to changes made to the project during construction. Changes made to the project are common during construction and it is important that the affect these changes have on comfort is quantified. For instance, changes in materials often occur during construction due to cost, lead time, etc. So, if a window type was changed from the type specified in the design then the CnCP captures the effect this change has on the comfort of the affected space.

3.2.3.7 Actual Comfort Performance (ACP)

The ACP quantifies the actual comfort levels achieved in the space. The comfort values for the Actual Comfort Performance are obtained in two stages, firstly using an appropriate measurement tool and then an appropriate calculation tool. The measurement tool records the CO_2 value and input environmental variables for the PPD. The personal variables for the PPD are either obtained from observation or from set standard values. The calculation tool uses this information to compute the PPD value. A standard spreadsheet application can be used as the calculation tool. However, prior to this research, no suitable measurement tool was available. The technology and system to measure actual comfort at appropriate locations, such as office desks, in a fully operational environment is not readily available. §4.3.3 describes the Egg-Whisk Network, which is the measurement tool developed by this research.

The time period over which data is recorded to development the ACP can vary. It can be a day, week, month, or it can be continuous. The greater the number of days that are analysed the more accurate the results become.

The ACP is important to ComMet as it is used to calibrate the Comfort Model. This calibrated Comfort Model then generates the Calibrated Comfort Performance, and is also used as the base model for all the proceeding operation stage models.

3.2.3.8 Calibrated Comfort Performance (CaCP)

The CaCP is generated from the calibrated Comfort Model. The Comfort Model is created by calibrating the simulated Comfort Model to match the actual comfort conditions using the ACP, the actual building information, and an appropriate calibration methodology, such as that specified by Hajdukiewicz et al [90] for CFD. The Calibrated Comfort Model is essentially a virtual test-bed for the model location. It should be noted that if the ACP is not available then this model is just a simulated model of the actual environment. It can still be used by the proceeding models but it is not as realistic or reliable. Apart from it being the base model for the proceeding operation models, it can also be used for future projects. For example, if a similar design is used in a future building a benefit can be achieved by using a calibrated simulation model as an initial design model.

Current calibration methodologies and technologies are still relatively new and immature but are improving. An essential ingredient required to improve calibration methodologies is measured data. In this respect ComMet and calibration methodologies are mutually beneficial to each other. ComMet provides the measured data necessary to improve calibrated simulation models and these calibrated simulation models can then be used by ComMet.

3.2.3.9 Optimum Comfort Performance (OCP)

The OCP quantifies the optimum or best possible comfort levels achievable within the actual environment using the HVAC systems. Since the CaCP might not quantify the environment's optimum comfort conditions, the Comfort Model is used to identify the environmental strategy that would provide the optimum comfort conditions. The OCP is created when the adjustable environmental parameters of the Comfort Model, such as heating strategy, are analysed and altered until the comfort conditions are optimised in the model. The identified optimum environmental strategy can then be adopted in the actual environment. For example, the OCP may identify that the optimum environmental strategy requires the heating timetable to be altered to achieve the optimum comfort conditions in the environment. A similar method to use calibrated whole building energy simulation models for performance optimisation has been proposed by Costa et al [91].

3.2.3.10 Control Comfort Performance (CrCP)

The CrCP quantifies the expected comfort levels based on the predicted environmental data and adjusted control strategy. This performance is used to quantify the success of the control strategies developed to deal with the varying environmental boundary conditions throughout the year. The performance is created by adjusting the Comfort Model by inputting the predicted boundary conditions, such as weather conditions. Then the adjustable environmental parameters of the model, such as the heating strategy, are analysed and altered until the best comfort conditions are achieved in the model. The identified control strategy can then be adopted in the actual environment. Based on predicted weather conditions, a control strategy may require that the heating timetable be altered to maintain comfort in the space. This becomes particularly useful when using a time lag system such as under-floor heating, where rapid control of environment temperature is not possible.

3.2.3.11 Historical Comfort Performance (HCP)

The HCP quantifies the expected comfort levels based on the historical environmental data and employed control strategy. This performance is used as a benchmark to identify operational errors and faults by comparing it with its equivalent ACP. The performance is created by adjusting the Comfort Model by inputting the appropriate boundary conditions, such as weather conditions, for a particular historical time. This HCP is then compared with the ACP for the same time and the differences are analysed to identify any errors or faults in the HVAC operation. An air quality difference between the HCP and the ACP could mean that there is a fault in the HVAC system. A similar method to use calibrated whole building energy simulation models for error detection has been proposed by Torrens et al [43].

3.2.3.12 Future Comfort Performance (FCP)

The FCP quantifies the expected comfort levels based on future design data for the current environment. This performance is used to predict the success of potential adjustments to the physical environment. It is created when the Comfort Model is adjusted to match the proposed physical changes of a future design. If the insulation level on an external wall was to be increased, this performance would predict the changes in comfort of the affected space. If the planned changes are to be implemented the FCP becomes the DCP for the new project that will implement the changes. The FCP of Project X is equivalent to the DCP of Project (X+1). A graphical representation of this is shown in Figure 3.7.

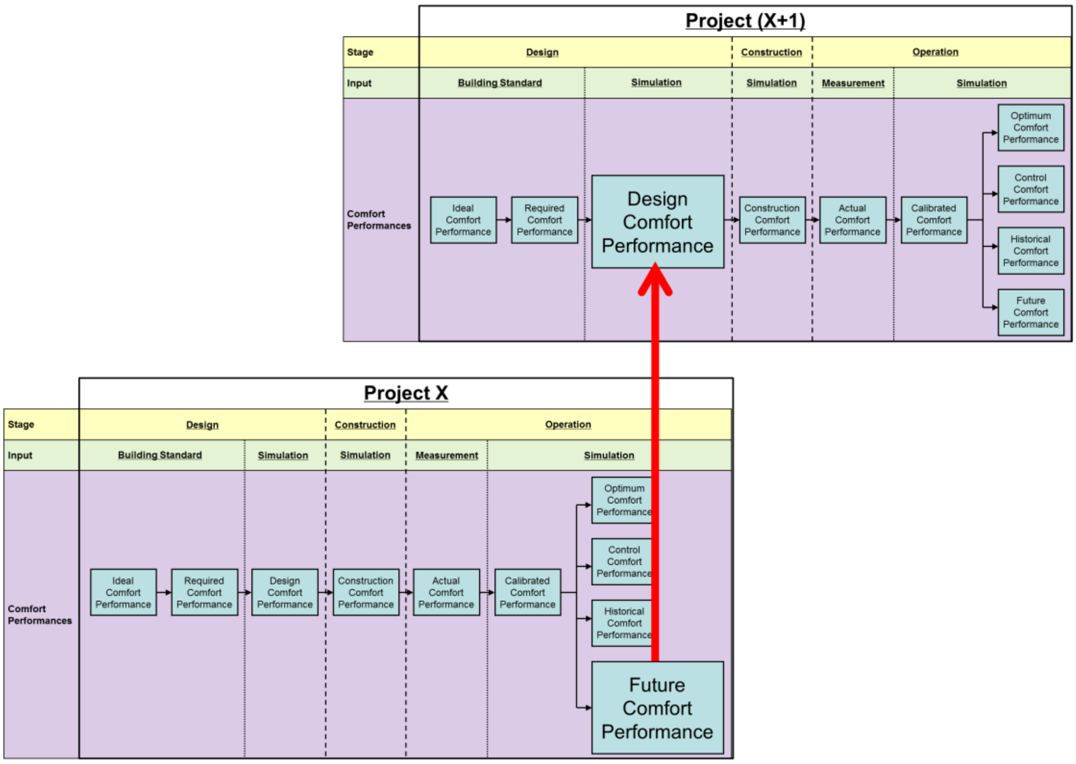

Figure 3.7 – The FCP and DCP Connection

3.2.3.13 Summary

A summary description of the Comfort Performances is given in Table 3.1.

Table 3.1 – Comfort Performance Descriptions

Comfort Model	Definition	Inputs Required	Creation Tool	Non-Model Outputs
Ideal Comfort Performance (ICP)	Ideal comfort levels that can be achieved	Building Standards	N/A	N/A
Required Comfort Performance (RCP)	Minimum required comfort levels to be achieved	Building Standards	N/A	N/A
Design Comfort Performance (DCP)	Expected comfort levels based on the design data	Comfort Model and Design Data	Simulation Tool + Calculation Tool	N/A
Construction Comfort Performance (CnCP)	Expected comfort levels based on the construction data	Comfort Model and Construction Data	Simulation Tool + Calculation Tool	N/A
Actual Comfort Performance (ACP)	Actual comfort levels achieved	<u>Stage 1:</u> Actual Environment	Measure-ment Tool	Actual Environ-mental Data

This table continues on the next page.

Comfort Model	Definition	Inputs Required	Creation Tool	Non-Model Outputs
This table starts on the previous page.				
		Stage 2: Actual Environ-mental Data and Building Data	Calculation Tool	N/A
Calibrated Comfort Performance (CaCP)	Simulated Comfort Performance calibrated to match the ACP	Comfort Model and the ACP	Simulation Tool + Calculation Tool	N/A
Optimum Comfort Performance (OCP)	The optimum comfort levels achievable with the actual environment and HVAC systems	Comfort Model and comfort strategies	Simulation Tool + Calculation Tool	Optimum Comfort Strategy
Control Comfort Performance (CrCP)	Expected comfort levels based on the predicted environmental data and adjusted control strategy	Comfort Model and predicted environment-al data	Simulation Tool + Calculation Tool	Control Strategy
This table continues on the next page.				

Comfort Model	Definition	Inputs Required	Creation Tool	Non-Model Outputs
This table starts on the previous page.				
Historical Comfort Performance (HCP)	Expected comfort levels based on the historical environmental data and employed control strategy	Comfort Model and historical environment-al data	Simulation Tool + Calculation Tool	N/A
Future Comfort Performance (FCP)	Expected comfort levels based on future design data for the current environment	Comfort Model and Future Design Data	Simulation Tool + Calculation Tool	N/A

3.2.4 Comfort Performance Production Scenario

This section describes a typical Comfort Performance production sequence, which is shown in Figure 3.8.

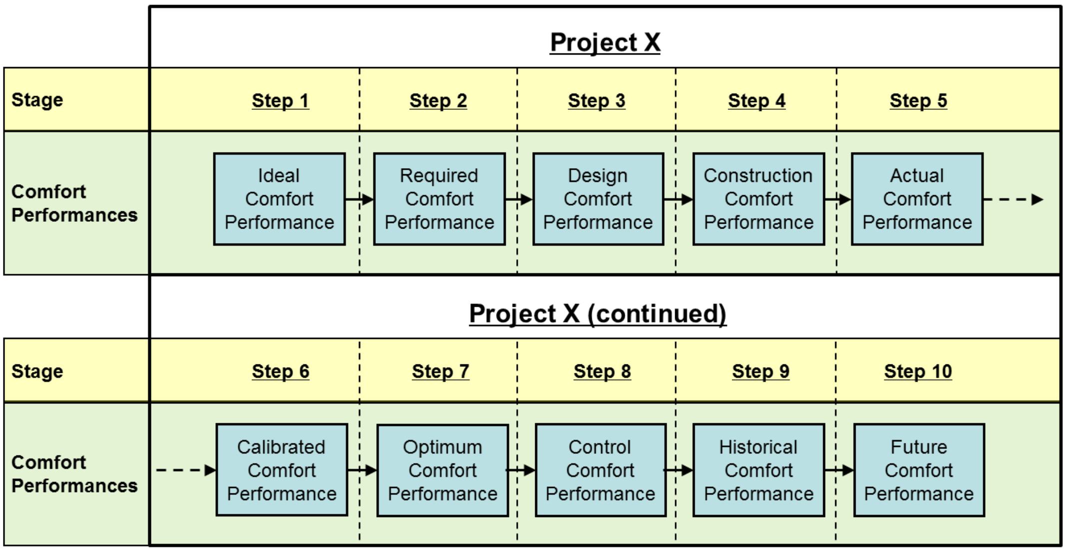

Figure 3.8 – Comfort Performance Production Scenario

3.2.4.1 Step 1 & 2 – The Building Standards

Once a project begins, the Designer starts to generate the Comfort Performances. The first two performances created are the ICP and RCP. The Designer generates these from information contained in the relevant building standards. Like the building standards, the ICP gives the Designer the best possible comfort level that can be achieved and the RCP gives the legally required comfort level that should be achieved. The ICP and RCP basically convert the information in the building standards into the Comfort Performance format so the building standards can be compared one-to-one with other Comfort Performances.

3.2.4.2 Step 3 – Design

The Designer then creates the design for the project. Using the appropriate simulation and calculation tools the Designer generates the Comfort Model. This generates the DCM, which quantifies the comfort level that will be achievable from the proposed design. The goal of the Designer is to have a DCP that is better than the RCP and as close to the ICP as possible. In other words, the Designer wants the design to be better than the legally required comfort level and very close to the best possible comfort level.

3.2.4.3 Step 4 – Construction

The project moves into the construction stage once the design is complete. Changes are inevitable during construction and the purpose of the CnCP is to quantify these changes. When a change is proposed during construction the Designer on the construction team generates the CnCP, which shows the affect the changes have on the comfort level compared to the other Comfort Performances. Quantifying the effects of the changes using the CnCP makes it easier to make more informed decisions during construction.

3.2.4.4 Step 5 – Measurement

After the construction is complete and the building is operational, a Designer on the building operation team generates the ACP. The Designer uses measurements of the actual environmental conditions to generate the ACP, which represents the actual comfort level in the environment being analysed.

3.2.4.5 Step 6 – Calibration

The next step in the process is to calibrate the Comfort Model. The Designer on the building operation team calibrates the Comfort Model, using the actual environmental data, to generate a CaCP that matches the ACP. The calibrated Comfort Model is a virtual model that mimics how the actual environment operates and allows the Designer to cheaply and quickly virtually experiment with the environment.

3.2.4.6 Step 7 – Optimisation of Comfort

One beneficial use of the Comfort Model is to identify the optimal HVAC strategy for the space. The Designer uses the Comfort Model and systematically alters the HVAC strategy to create the optimum comfort conditions in the space. The Comfort Model using the optimum HVAC strategy generates the OCP. This new strategy can then be used for the actual operation of the environment, if required.

3.2.4.7 Step 8 – Controlling Comfort

Another use for the Comfort Model is to control the operation of the HVAC system. The Designer can alter the Comfort Model by using the predicted factors that affect the environmental conditions in the space, such as the forecasted external temperature or the expected number of occupants for the following day, and then identify the most suitable control strategy for that day. The performance generated by this Comfort Model is the CrCP. In a space that uses under-floor heating, if a low external temperature is forecast for the following day, the heating system could be started earlier to ensure acceptable comfort.

3.2.4.8 Step 9 – Fault Detection

The Comfort Model can be used to detect faults in the operation of HVAC system. First, the Designer chooses a past (historical) day to analyse. Then they alter the Comfort Model to use the control strategy used on that day, that is, those conditions that the HVAC system specified it supplied to the environment on that day. The Designer alters the Comfort Model to use the environmental factors from the same day such as occupant numbers, external temperature, etc. The performance generated by this Comfort Model is the HCP. This HCP is then compared to the ACP from the same day, and if there is any difference between them, the Designer knows that there is discrepancy or error in the operation of the HVAC system. If there is any difference between what was predicted and what was measured there is a problem. If these problems are not extreme they can exist unbeknownst to the occupants. If the HVAC system is reporting that it is supplying heat to a space but the comfort in the space does not match what would be expected from that heat supply then a window might be jammed open.

3.2.4.9 Step 10 – Into the Future

Since the Comfort Model is a virtual test-bed for the environment, it can be used to trial alterations. The Designer can simulate the effects making structural changes to the environment would have on the comfort before carrying them out. The performance generated by this Comfort Model is the FCP. If the alterations are carried out, the FCP essentially becomes a DCP for a new project and the sequence can begin again.

3.2.5 Comfort Ratings

3.2.5.1 General

The Comfort Ratings are a means of classifying the comfort of the indoor environment according to a suitable standard. Since comfort is quantified by the Comfort Performances, the Comfort Ratings are generated from comparing different Comfort Performances. They provide extra information on the comfort of the indoor environment, which is not easily determinable from the individual performances. The information is clear, unambiguous, and requires little comfort knowledge to understand. The comparisons translate the complex definitions of comfort in the Comfort Performances into universally understandable ratings which are usable by the expert and non-expert alike.

The ratings are in the form of:

$$Z = \frac{X\ (dividend)}{Y\ (divisor)} \qquad (3.1)$$

Where:

- Z is the rating. It is the unit-less ratio of X to Y;
- X is the dividend Comfort Performance. It is the base performance that the divisor performance is to be compared to;
- Y is the divisor Comfort Performance. It is the Comfort Performance that is to be compared to the base performance.

In other terms:

$$\textit{Comfort Rating} \quad = \quad \frac{\textit{Comfort Performance (dividend)}}{\textit{Comfort Performance (divisor)}} \qquad (3.2)$$

For *Comfort Rating = 1*:

The divisor Comfort Performance and dividend Comfort Performance are equivalent.

For *0* < *Comfort Rating* < *1*:

The divisor Comfort Performance is worse than the dividend Comfort Performance. The further from 1 the rating is the worse the divisor Comfort Performance is.

For *1* < *Comfort Rating*:

The divisor Comfort Performance is better than the dividend Comfort Performance. The further from 1 the rating is the better the divisor Comfort Performance is.

The main benefits of using ratios for these ratings are:

- They are unit-less. This means that the non-expert does not need to understand the details of PPD or CO_2 and how they are quantified;
- All the ratings are relative to the same base value, which is 1. The non-expert does not need to know different optimum values for PPD and CO_2. The non-expert does not need to know that the ideal PPD value is 5% and the ideal CO_2 is 750ppm and that these are minimum values. The ratings change the two different measurement units, '%' & 'ppm', and the two different optimum values, 5% & 750ppm, into one optimum value, 1, which dramatically reduces the complexity;

- The ratings are greater than the sum of their parts. Viewing some of the Comfort Performances individually can be uninformative. If they are compared in the rating format then useful unambiguous information can be generated. The comfort expert knows which models to compare to obtain useful information. ComMet captures this knowledge and adds it to the Comfort Performances to create these ratings so the non-expert can obtain this useful information. Knowledge can be gained from the ACP and OCP independently. Comparing these performances creates new information about how well the environment is being operated, as the closer the actual comfort is to the optimum comfort the better the environment is being operated. See §3.2.5.4 for a more detailed explanation of this.

The definition of comfort used in this research will inevitably be expanded to include other comfort parameters, such as acoustics and lighting, which only compounds the benefits of using these ratings as the ratings remove the need to understand the details of these parameters. Difficulties arise when visually displaying a Comfort Performance with more than two parameters. If the Comfort Model includes more than two different parameters then it cannot be clearly displayed on a standard bar-chart as it would require more than two vertical axes. Common charting tools, such as Microsoft Excel, do not have the functionality to include more than two vertical axes. These charting tools are used throughout the industry, and requiring that these tools be changed to accommodate this new methodology would not satisfy the BabySteps approach. The ratings are primarily used to allow the non-expert get an understanding of comfort, and allow the comfort knowledge be re-used by interested parties other than just comfort experts.

Because this research is using sets, the Comfort Rating will be a set of ratios; one for the PPD and one for the CO_2 value. It will be written in the format ([ratio]PPD, [ratio]CO_2) e.g (0.5PPD,0.75CO_2).

If an environment had an Ideal Comfort Performance of (5%,750ppm) and a Design Comfort Performance of (15%,1000ppm) then comparing the design to the ideal will yield (0.33PPD,0.75CO_2), which shows that the design performance is worse than the ideal performance for both thermal conditions and air quality.

The fundamental Comfort Performance is a performance of a single point and, therefore, the fundamental Comfort Rating is of a single point. A combination of these single point ratings forms a space rating. In practical terms, since comfort is only relevant to occupants, the single point will be the location of an occupied point such as a desk and the space rating will be a room or a building as shown in Figure 3.9. Therefore, desk Comfort Ratings can be combined to form a room Comfort Rating and room Comfort Ratings can be combined to form a building Comfort Rating and so on. The average of the desk Comfort Ratings would be taken as the room Comfort Rating. ComMet is flexible enough to be used to monitor comfort of a desk, room, building, or building portfolio.

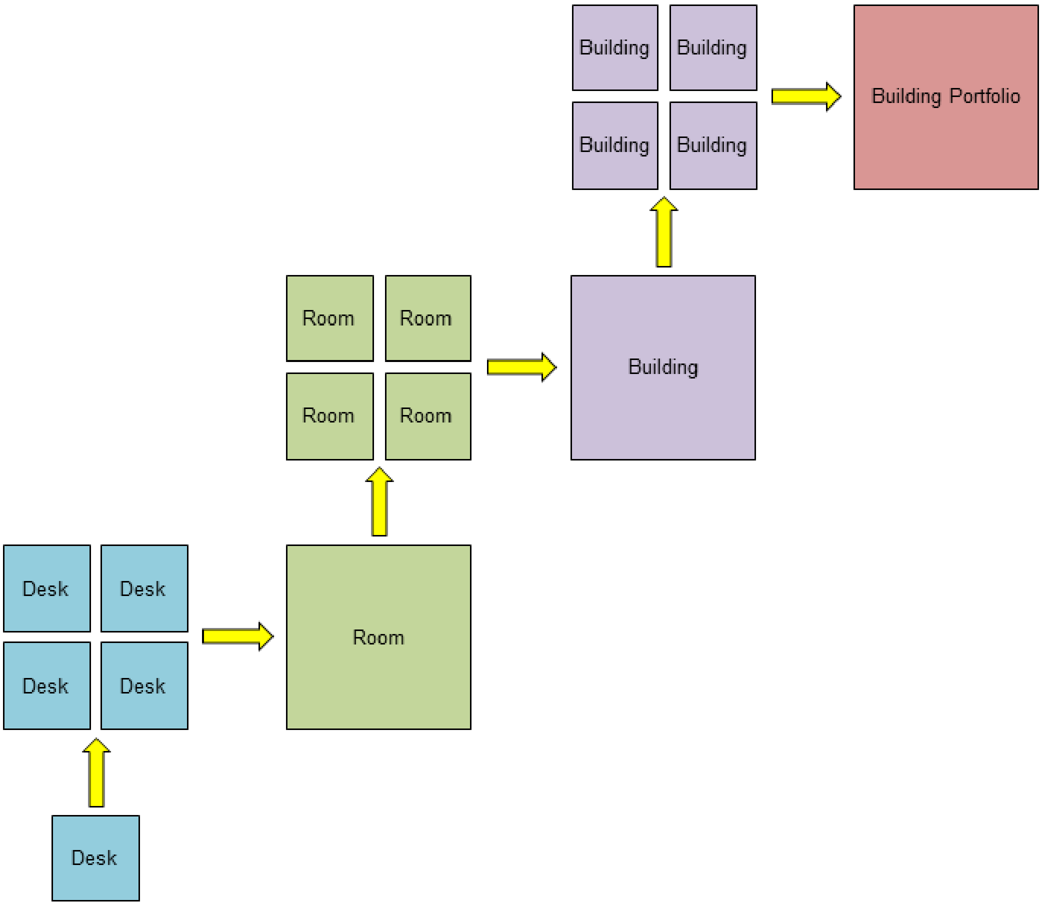

Figure 3.9 – Comfort Rating Connections

Comfort Rating bands were set up to clarify the classification of the Comfort Ratings whose values are greater than 0 and less than or equal to 1. The range from 0 to 1 is divided into 5 bands named A to E. The depth of the bands is based on percentage of buildings. The top 20% of buildings comprise band A, the next 20% comprise band B, and so on. However, since surveys of numerous buildings are required to generate these percentages, for the purpose of this research arbitrary limits are attributed to the bands, which are as follows:

- Band A = 1 – 0.8;
- Band B = 0.8 – 0.6;
- Band C = 0.6 – 0.4;
- Band D = 0.4 – 0.2;
- And band E = 0.2 – 0.0.

A graphical representation of the bands is shown in Figure 3.10.

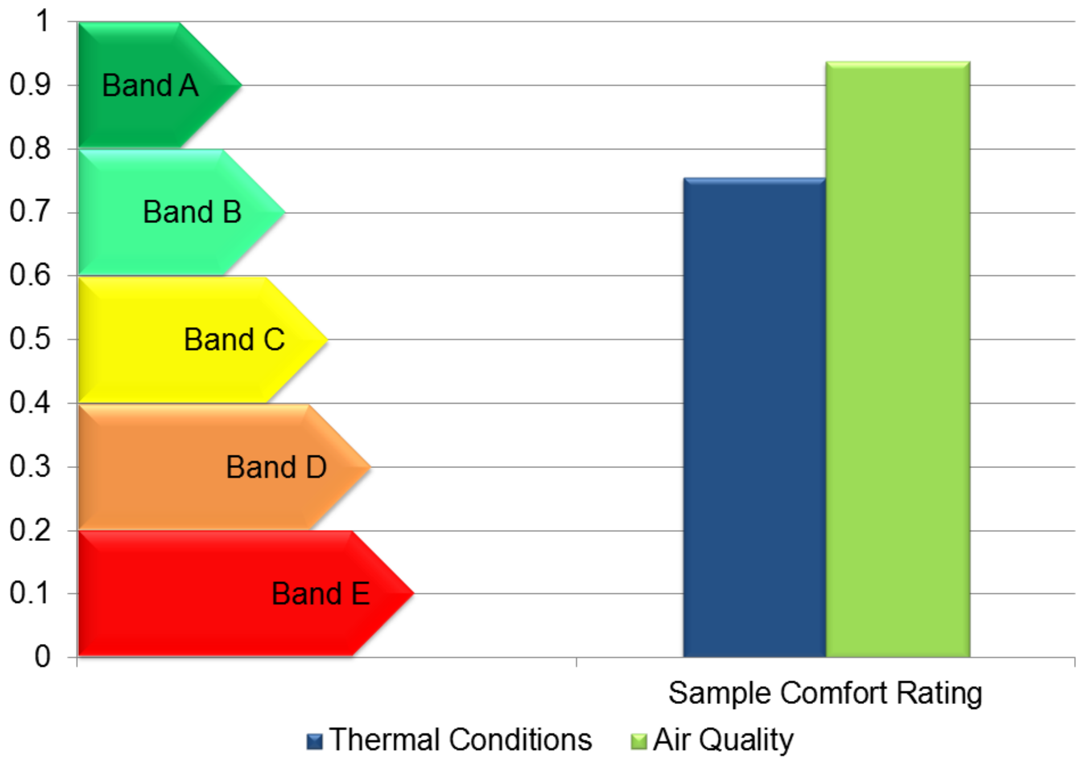

Figure 3.10 – Rating Bands

The banded rating system also satisfies BabySteps. This is because it is already an established metaphor for communicating levels of performance and has an instantly recognisable graphic. It is used throughout the world for communicating the energy performance of electrical products and buildings and so using a similar concept for communicating the comfort performance of buildings will not require a conceptual shift on the part of the building stakeholder. This allows the communication of the complex comfort entity to be simplified further, from Comfort Performance to Comfort Rating to Banded Comfort Rating. This means that the Banded Comfort Ratings can also be expressed using their simplified alphabetic values. For example a Comfort Rating of (0.9PPD, 0.7CO_2) could also be expressed as (A [PPD],B [CO_2]). The banded rating system would provide the basis for a Comfort Labelling System. A sample of one is shown in Figure 3.11.

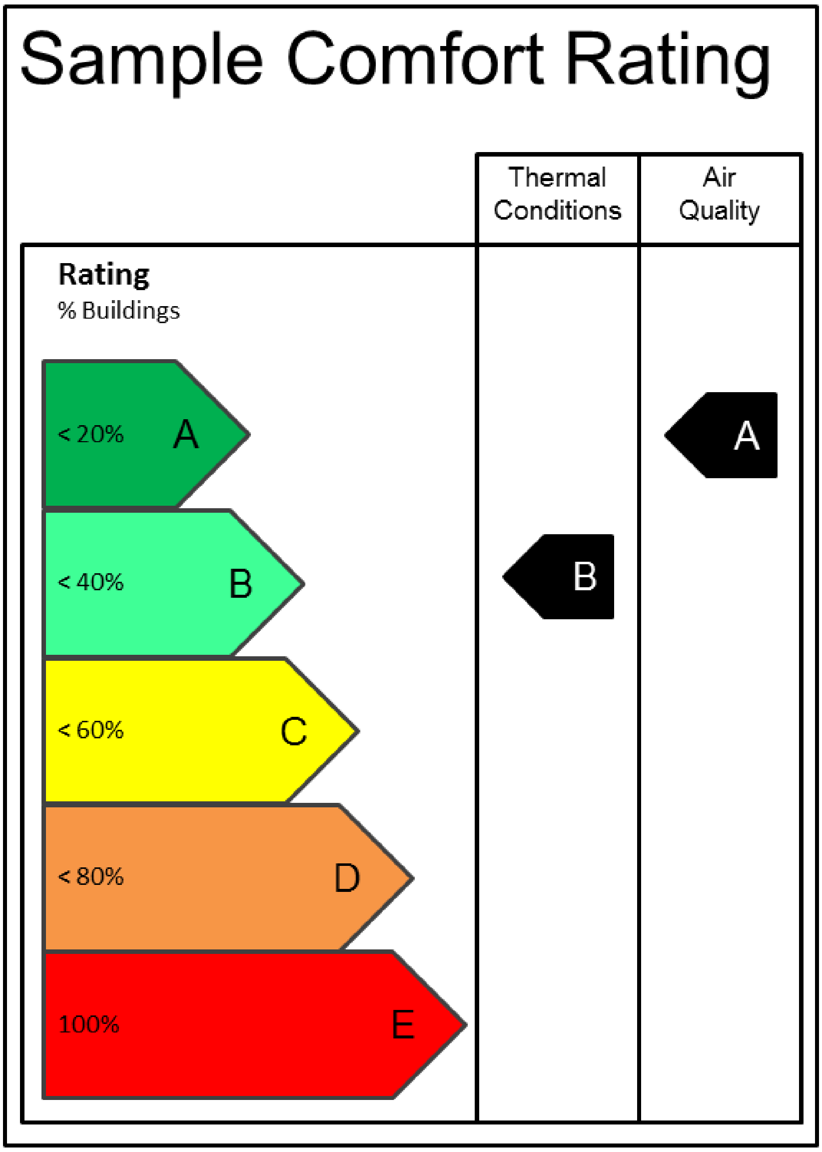

Figure 3.11 – Comfort Label

Seven Comfort Ratings were created for this research and the sequence in which they are created during a project is shown in the Figure 3.12. Two of the ratings have different versions depending on the BLC stage. The Project

Success Rating has a predicted version at the construction stage and an actual version at the operation stage. The Comfort Rating has six different versions throughout the BLC. The ratings are divided into the three project stages, design, construction and operation. They are sub-divided into Comfort Ratings, whose values are greater than 0 and less than or equal to 1, and Comfort Ratings whose values are greater than 0 and have no upper limit. §3.2.5.2 to §3.2.5.8 describe each of these ratings in detail.

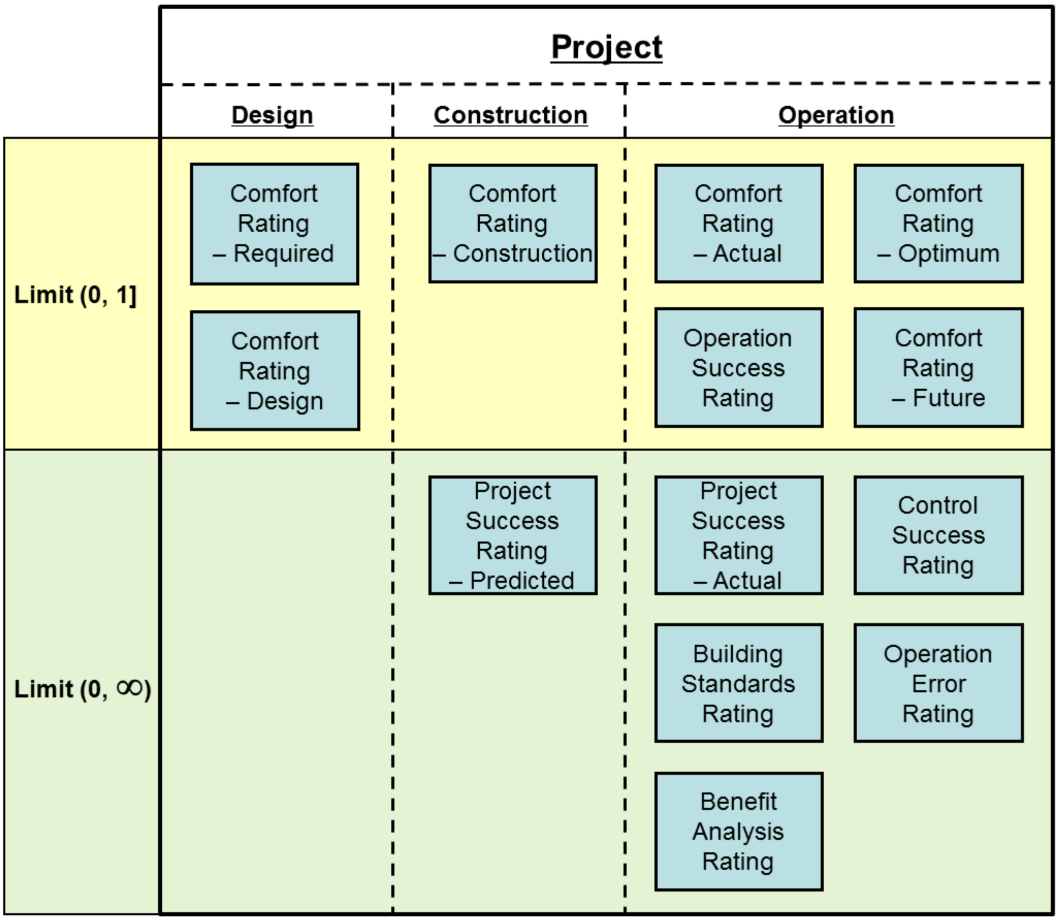

Figure 3.12 – Comfort Rating Creation Sequence

3.2.5.2 Comfort Rating (CR)

The CR classifies the comfort of the indoor environment at each stage of the building life-cycle. This allows the comfort to be monitored as the building project progresses. The CR compares the Comfort Performances at each stage to the Ideal Comfort Performance to generate a rating of greater than 0 and less than or equal to 1. There are six versions of the CR and they are described in §3.2.5.2.1 to §3.2.5.2.6.

3.2.5.2.1 Comfort Rating – Required (CR-R)

$$CR\text{-}R = \frac{\text{Ideal Comfort Performance}}{\text{Required Comfort Performance}} \tag{3.3}$$

This is the Comfort Rating required by building standards. It compares the required performance to the ideal performance. This converts the RCP into the Comfort Rating format that enables other Comfort Ratings to be compared to what is required by the building standards.

3.2.5.2.2 Comfort Rating – Design (CR-D)

$$CR\text{-}D = \frac{\text{Ideal Comfort Performance}}{\text{Design Comfort Performance}} \tag{3.4}$$

This is the Comfort Rating at the design stage. It compares the design performance to the ideal performance. It shows how close the DCP is to the ICP and is a measurement of the standard of the design.

3.2.5.2.3 Comfort Rating – Construction (CR-C)

$$CR\text{-}C = \frac{\text{Ideal Comfort Performance}}{\text{Construction Comfort Performance}} \tag{3.5}$$

This is the Comfort Rating at the construction stage. It compares the construction performance to the ideal performance. It shows how close to the ideal the construction is.

3.2.5.2.4 Comfort Rating – Actual (CR-A)

$$CR\text{-}A = \frac{\text{Ideal Comfort Performance}}{\text{Actual Comfort Performance}} \tag{3.6}$$

This is the Comfort Rating for the actual operation. It compares the actual performance to the ideal performance. It shows how close to the ideal the actual operation is.

3.2.5.2.5 Comfort Rating – Optimum (CR-O)

$$CR\text{-}O = \frac{\text{Ideal Comfort Performance}}{\text{Optimum Comfort Performance}} \tag{3.7}$$

This is the Comfort Rating for the optimum performance. It compares the optimum performance to the ideal performance. It shows how close to the ideal the optimum is, or how close to ideal comfort conditions the comfort at the specified location can ever reach.

3.2.5.2.6 Comfort Rating – Future (CR-F)

$$\textit{CR-F} = \frac{\textit{Ideal Comfort Performance}}{\textit{Future Comfort Performance}} \tag{3.8}$$

This is the Comfort Rating for the future design. It compares the future performance to the ideal performance. It shows how close to the ideal the future design is. This enables an easy comparison between future design options.

3.2.5.3 Project Success Rating (PSR)

There are two versions of the PSR, which are described in §3.2.5.3.1 and §3.2.5.3.2.

3.2.5.3.1 Project Success Rating – Predicted (PSR-P)

$$\textit{PSR-P} = \frac{\textit{Design Comfort Performance}}{\textit{Construction Comfort Performance}} \tag{3.9}$$

This compares the construction to the design. It predicts how successful the project will be at achieving the design intent. A value of below 1 predicts that the project will under achieve the level of comfort predicted by the design, and a value above 1 predicts that the project will over achieve the predicted comfort in the space. It is a prediction because the Construction Comfort Performance is generated by the un-calibrated Comfort Model.

3.2.5.3.2 Project Success Rating – Actual (PSR-A)

$$\textit{PSR-A} = \frac{\textit{Design Comfort Performance}}{\textit{Optimum Comfort Performance}} \tag{3.10}$$

This compares the optimum to the design. It shows the success of the project, or how good the project was at actually achieving the level of comfort predicted by the design. It is an actual classification because the Optimum Comfort Performance is generated by the calibrated Comfort Model.

3.2.5.4 Operation Success Rating (OSR)

$$OSR = \frac{\textit{Optimum Comfort Performance}}{\textit{Actual Comfort Performance}} \qquad (3.11)$$

This compares the actual to the optimum. This shows the success of the operation. This rating allows the comparison of the operation of different buildings. If Building A had a better ACP than Building B then it is often assumed that Building A is operated better than Building B. However if the difference between Building A's ACP and OCP is much greater than Building B's, this shows that Building B is actually operating better. This can often be the case when comparing buildings of different ages. The OSR identifies this fact and so gives a better measurement of the relative operation of buildings. Figure 3.13 shows the ACPs and OCPs of three hypothetical buildings. From this chart it is unclear as to the relative operational performance of each building. Figure 3.14 shows the OSRs of each building and it clearly shows that Building C is operating the best, Building A is second despite having the worst ACP, and Building B is last.

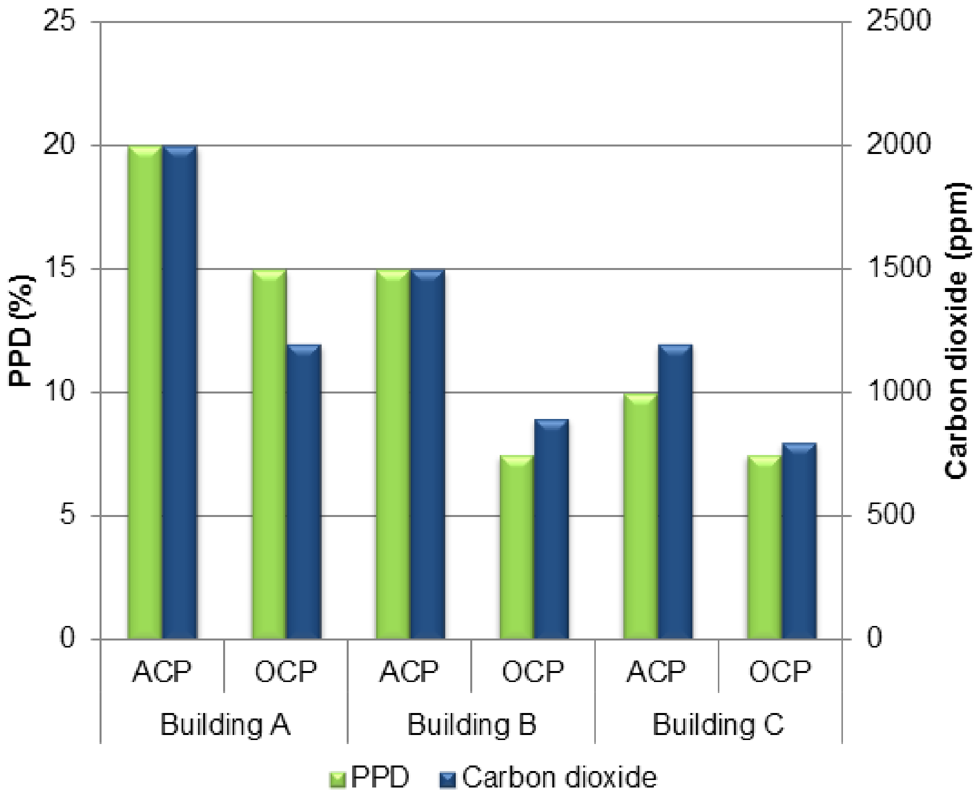

Figure 3.13 – Comparison of Buildings' Operational Performance using their ACPs and OCPs

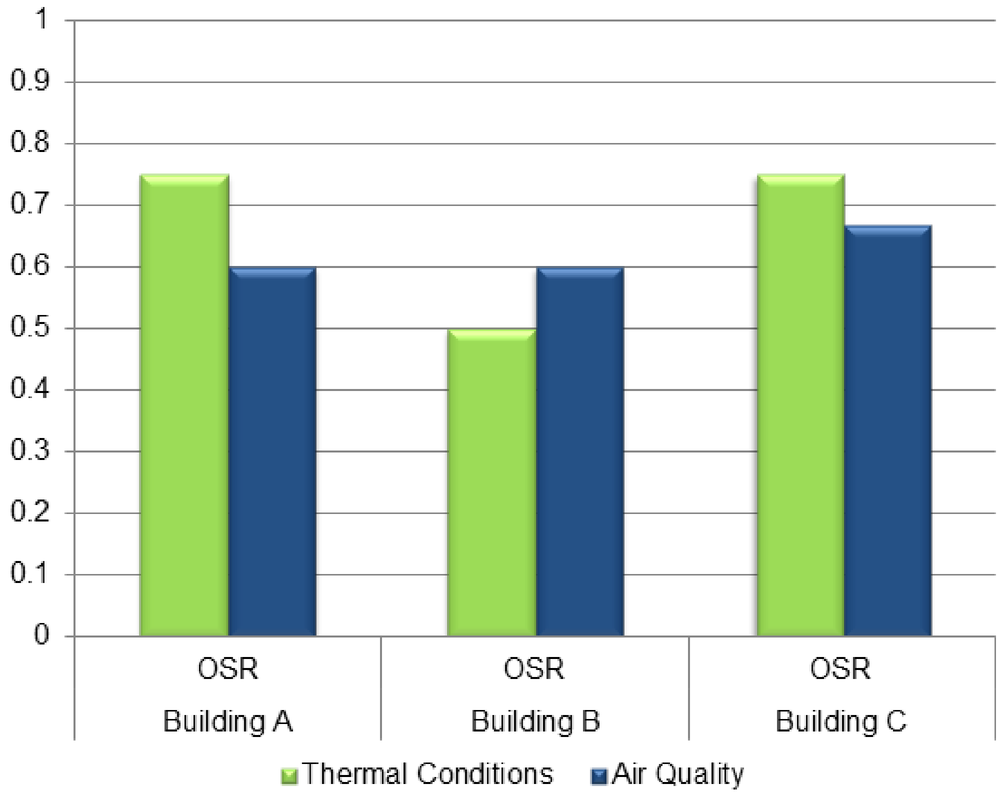

Figure 3.14 – Comparison of Buildings' Operational Performance using their OSRs

3.2.5.5 Control Success Rating (CrSR)

$$CrSR = \frac{\text{Control Comfort Performance}}{\text{Actual Comfort Performance}} \tag{3.12}$$

This compares the actual to the control. It shows how good the Comfort Model was at predicting the comfort levels. This is very beneficial because the best achievable comfort levels under different environmental boundary conditions will vary but the CrSR will always show the accuracy of the Comfort Model at predicting the comfort conditions. This allows the accuracy of the CrCP to be clearly monitored. Figure 3.15 shows the CrCP for a hypothetical building for three days. The purpose of the CrCP is to predict the comfort, however, despite this no information on the accuracy of the CrCP is determinable from this chart, which fully displays the CrCP. Even when the CrCP is graphed with the ACP, as in Figure 3.16, the accuracy of the CrCP is unclear. Using the CrSR, Figure 3.17 clearly shows that the CrCP is improving over the three days. This highlights the benefits of using the Control Success Rating.

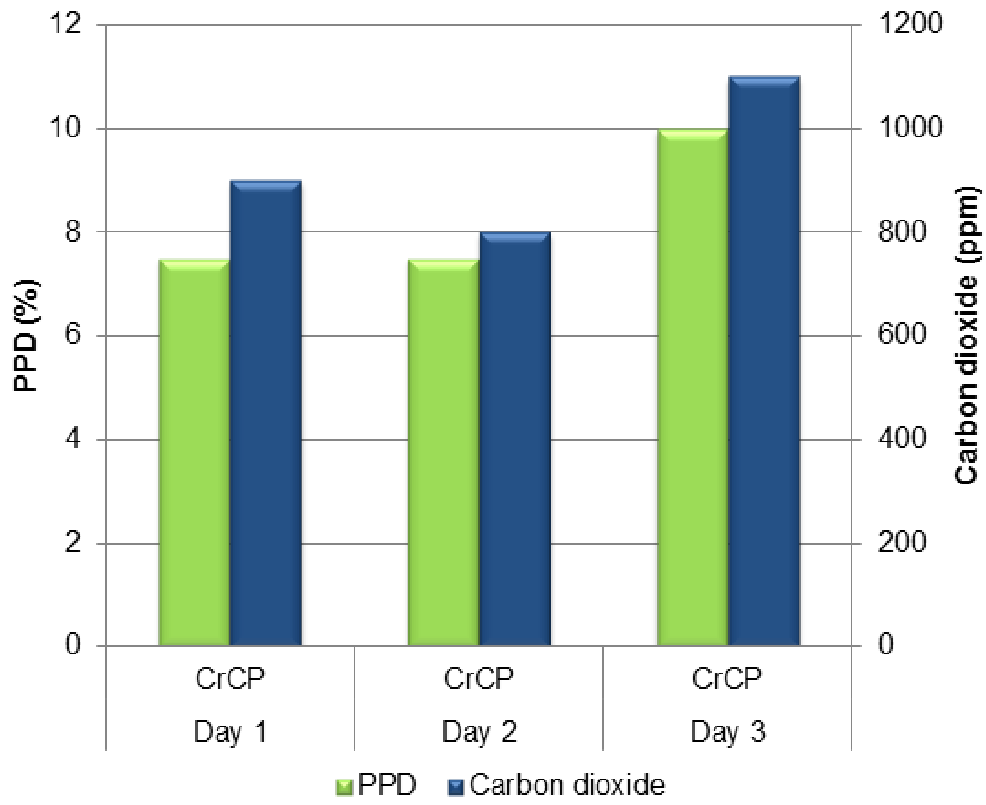

Figure 3.15 – Comparison of the CrCP of a Building for Three Days

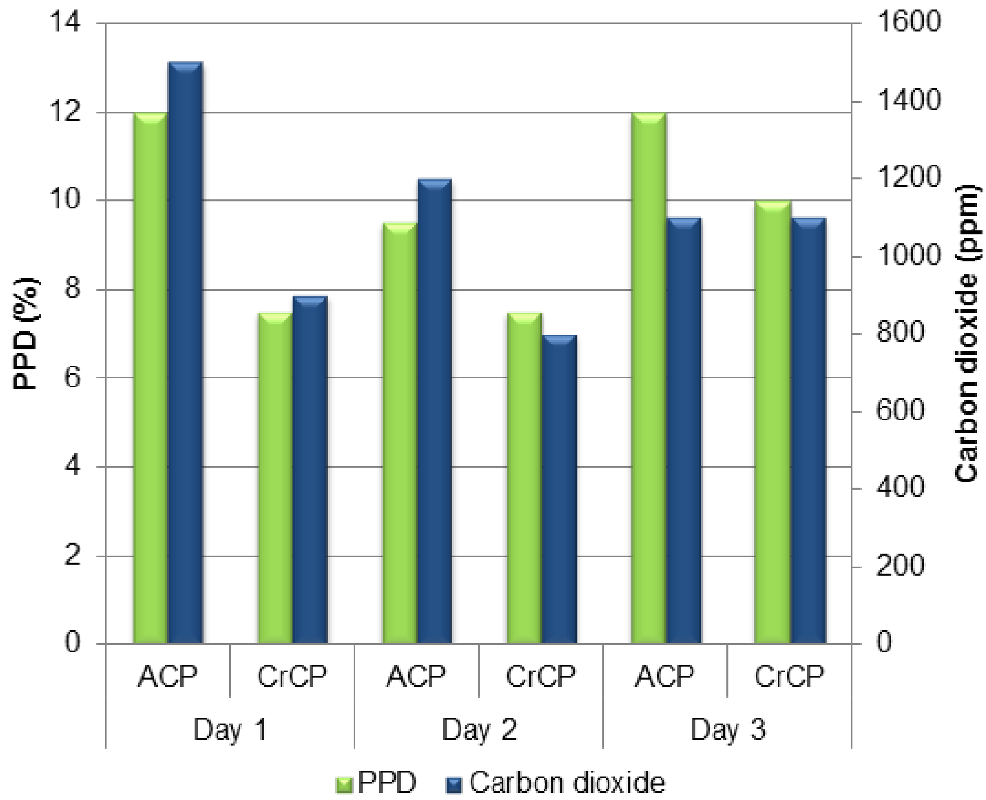

Figure 3.16 – Comparison of the ACP and CrCP of a Building for Three Days

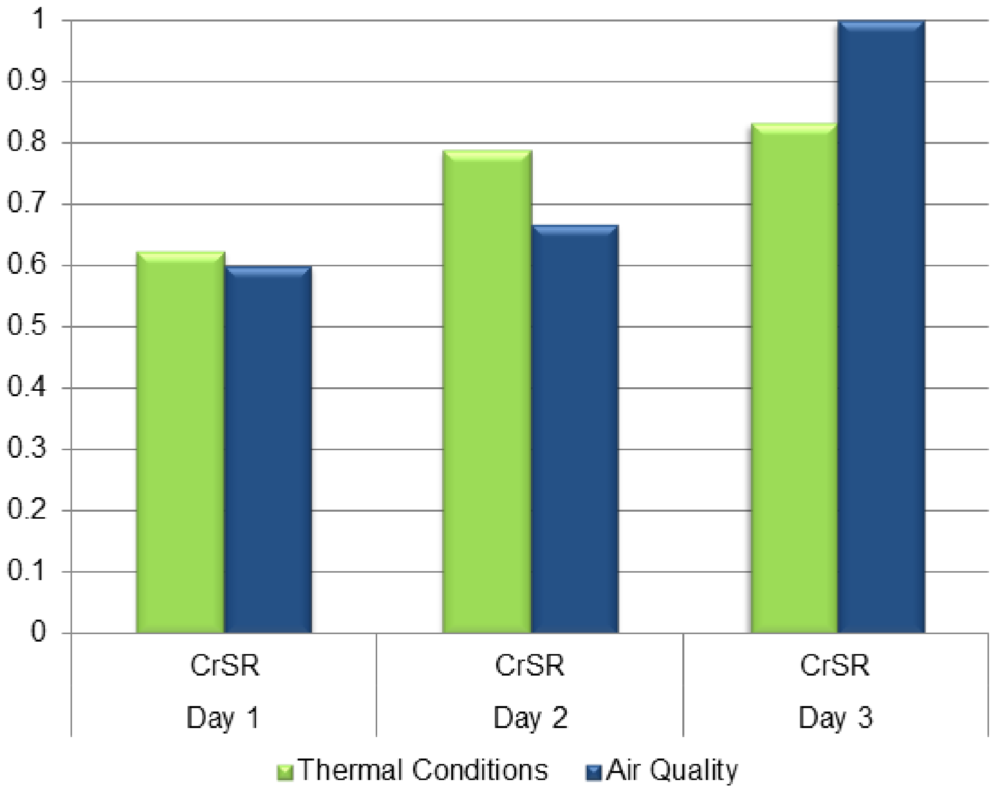

Figure 3.17 – Comparison of the CrSR of a Building for Three Days

3.2.5.6 Building Standards Rating (BSR)

$$BSR = \frac{\textit{Required Comfort Performance}}{\textit{Actual Comfort Performance}} \tag{3.13}$$

This compares the actual to the required. It shows the degree to which the building standards are being complied with. Buildings are designed to meet certain prescribed standards based on typical boundary conditions. This rating can give a measurement of how well the actual comfort conditions comply with the building standards based on the actual boundary conditions experienced by the building.

3.2.5.7 Operation Error Rating (OER)

$$OER = \frac{\textit{Historical Comfort Performance}}{\textit{Actual Comfort Performance}} \tag{3.14}$$

This compares the actual to the historical. The simulated HCP acts as a benchmark for the ACP for the same specified time and any difference outside a defined tolerance signifies an error in some part of the HVAC operation.

3.2.5.8 Benefit Analysis Rating (BAR)

$$BAR = \frac{\textit{Optimum Comfort Performance}}{\textit{Future Comfort Performance}} \qquad (3.15)$$

This compares the future performance to the optimum. It shows the benefit of making the proposed design changes.

3.2.5.9 Summary

A summary of the Comfort Ratings is given in Table 3.2.

Table 3.2 – Comfort Ratings produced from Comfort Performance comparisons

Rating	Definition	Dividend Comfort Performance	Divisor Comfort Performance
Comfort Rating – Required (CR-R)	The comfort level required by the building standards.	Ideal	Required
Comfort Rating – Design (CR-D)	How close the Design Comfort Performance is to the Ideal Comfort Performance	Ideal	Design
Comfort Rating – Construction (CR-C)	How close the Construction Comfort Performance is to the Ideal Comfort Performance	Ideal	Construction
Comfort Rating – Actual (CR-A)	How close the Actual Comfort Performance is to the Ideal Comfort Performance	Ideal	Actual
Comfort Rating – Optimum (CR-O)	How close the Optimum Comfort Performance is to the Ideal Comfort Performance	Ideal	Optimum
This table continues on the next page.			

Rating	Definition	Dividend Comfort Performance	Divisor Comfort Performance
This table starts on the previous page.			
Comfort Rating – Future (CR-F)	How close the Future Comfort Performance is to the Ideal Comfort Performance	Ideal	Future
Project Success Rating – Predicted (PSR-P)	The predicted success of the project at achieving the level of comfort predicted by the design.	Design	Optimum
Project Success Rating – Actual (PSR-A)	The actual success of the construction at achieving the level of comfort predicted by the design.	Design	Construction
Operation Success Rating (OSR)	The success of the operation.	Optimum	Actual
Control Success Rating (CrSR)	The accuracy of the Control Comfort Performance at predicting the comfort levels.	Control	Actual
This table continues on the next page.			

Rating	Definition	Dividend Comfort Performance	Divisor Comfort Performance
This table starts on the previous page.			
Building Standards Rating (BSR)	The degree to which the building standards are being complied with.	Required	Actual
Operation Error Rating (OER)	The level of errors in the operation	Historical	Actual
Benefit Analysis Rating (BAR)	The benefit of making the proposed design changes.	Optimum	Future

3.2.6 Comfort Rating Production Scenario

This section describes a typical Comfort Performance and Comfort Rating production sequence which is shown in Figure 3.18.

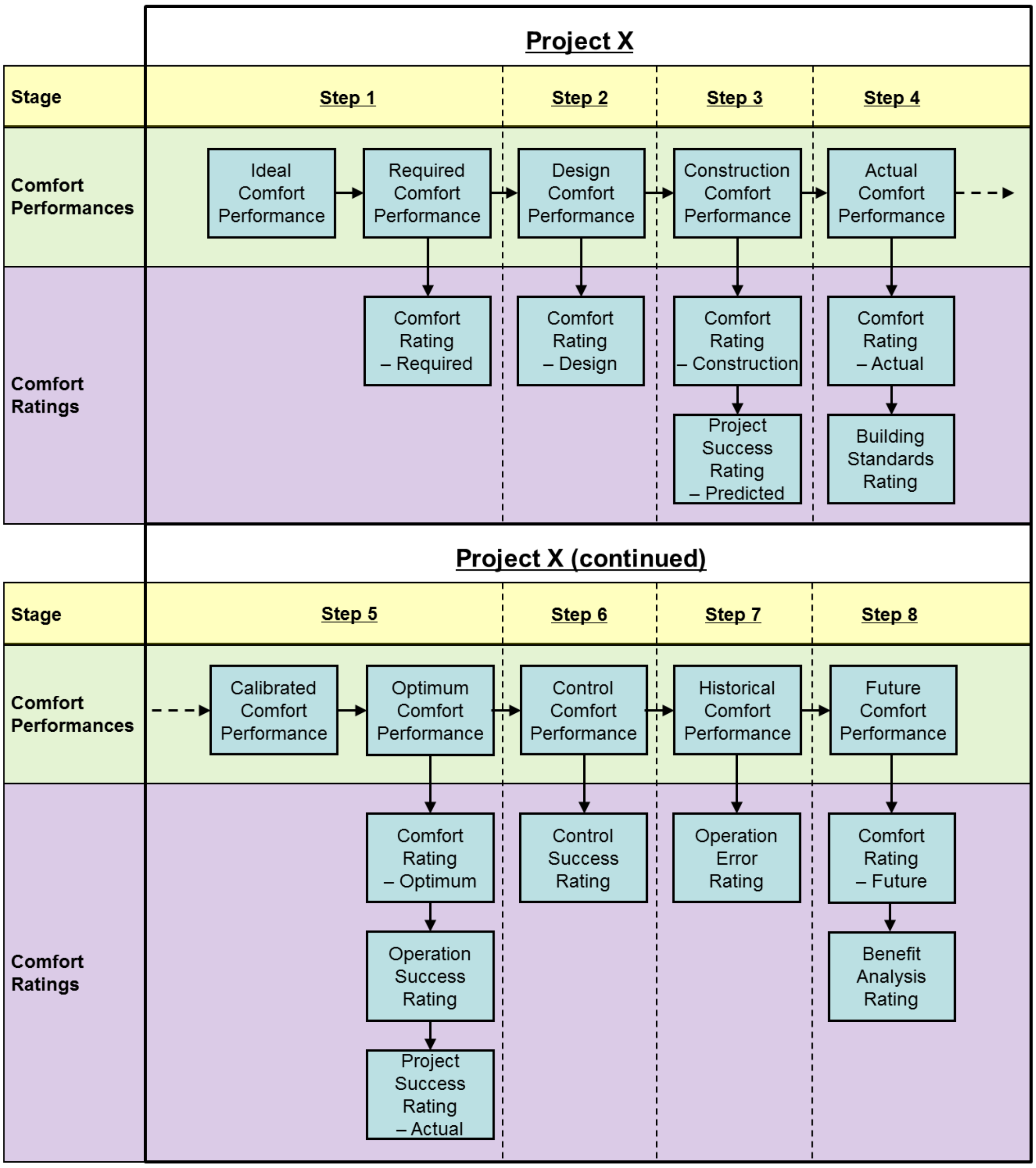

Figure 3.18 – Comfort Rating Production Scenario

3.2.6.1 Step 1 – The Building Standards

When a project begins, the Designer starts to generate the Comfort Performances. The first two performances created are the ICP and RCP. Once these are created the CR-R can be generated. The CR-R shows the Designer the minimum required standards to be met as per the building standards. The CR-R basically converts the RCP into the Comfort Rating format so other Comfort Ratings can be compared one-to-one with the requirements in the building standards.

3.2.6.2 Step 2 – Design

The Designer then creates the design and the DCP for the project. The Designer can then generate the CR-D. This classifies the comfort level that will be achievable from the proposed design. The goal of the Designer is to have a CR-D, which is better than the CR-R and as close to 1 as possible. In other words, the Designer wants the design to be better than the legally required comfort level and very close to the best possible comfort level.

3.2.6.3 Step 3 – Construction

During construction the CR-C is generated. This allows the Designer on the construction team to classify the comfort level after any changes that are proposed or made during construction. Classifying the effects of these changes enables the Project Manager to track the progress of comfort during construction and to make more informed decisions during construction.

Once construction is complete the PSR-P is generated. This predicts the success of construction at creating the environment as per the design. This informs the construction team and the Project Manager on the predicted success of the construction process. The goal for the construction process is to keep the PSR-P as close to 1 as possible as this predicts the construction process implemented the design accurately.

3.2.6.4 Step 4 – Operation

When the building is operating, a Designer on the building operation team generates the CR-A. The Designer uses this to classify the actual comfort level in the environment being analysed.

The Designer can generate the BSR. If the value of the BSR is below 1 then the environment is not meeting minimum comfort level as set by the building standards. This can be used by the Operator to warn him if the comfort level drops below the legally required limits.

3.2.6.5 Step 5 – Optimal Operation

Once the OCP is available, three new Comfort Ratings can be generated; the CR-O, OSR and PSR-A. The CR-O classifies the comfort level of the environment when it is operated at its optimum. It is essentially the result of the design and construction process, that is, it is what the environment produced can achieve. The CR-O is the maximum achievable comfort level of the environment and can be used as a classification of the quality of the environment in terms of comfort.

The OSR classifies the operational performance of the environment irrespective of its type, age, quality, etc., because the OSR is relative to the building's individual operational ability. Therefore, it can be used to compare the operation of different buildings. It can be used by the Owner to check how well the building operation team is operating the environment. Thresholds could be set for the building operation team whereby the owner could require that all the building environments must be operated above a defined OSR value. And, conversely, it can be used by the building operation team as a measure of the quality of their performance.

The PSR-A classifies the success of the design and construction process. It can be used by the Project Manager to measure how well the design and construction team performed.

3.2.6.6 Step 6 – Control Success

The CSR classifies the accuracy of the CrCP at predicting the comfort of the environment. It allows the Operator to identify if the strategy at producing the CrCP needs to be altered.

3.2.6.7 Step 8 – Fault Detection

The OER is generated once the HCP is available. It classifies any discrepancies between the actual comfort of the environment and the comfort simulated by the Comfort Model, i.e. the HCP. If the HCR is not within a predefined acceptable range of 1 then the operator knows that there is a fault in the operation of the HVAC system.

3.2.6.8 Step 9 – Into the Future

The final two Comfort Ratings to be generated are the CR-F and the BAR. When changes are proposed to the environment, such as changing its use, layout, ventilation, etc., and these changes are quantified by the FCP, the

CR-F classifies the comfort level provided by the changes. This allows the Designer or Operator to make informed decisions about the changes.

The BAR has a similar purpose to the CR-F but it classifies the comfort of the proposed changes relative to the current optimum comfort. This means that if the BAR is greater than 1, the proposed changes will improve on the current best possible comfort achievable in the environment.

3.2.7 Comfort History

'Progress, far from consisting in change, depends on retentiveness. When change is absolute there remains no being to improve and no direction is set for possible improvement: and when experience is not retained, as among savages, infancy is perpetual. Those who cannot remember the past are condemned to repeat it.' - George Santayana (philosopher, essayist poet, and novelist).

The concepts, decisions, and other experiences during a project are a valuable source of knowledge. This is probably the simplest part of ComMet and yet could easily be the most beneficial. The Comfort History is created by continuously recording descriptions of the experiences that affect comfort, storing them in a single location, and linking the recordings with the comfort entity that is affected by it, e.g. a Comfort Performance. An example of this is associating an explanation of the design intent and philosophy with the Design Comfort Performance, which allows a person reviewing the Design Comfort Performance to quickly see what the design was intended for or why certain design decisions were made. Otherwise, if this information is not stored and made accessible to future project stages and future projects then it is destined to be lost and will have to be recreated when it is required again e.g. when a heating system has to be reverse engineered to discover its unrecorded design intent.

The core aspect of this is that the information that exists, and is usually recorded, is firstly stored in an accessible location. Information that is not to be directly used in future stages of the project is often just stored by the creator. The reason for choosing a particular heating system is usually not linked to the design and transferred on to future stages as it is not a requirement for the installation of the heating system, which is usually the immediate next step. However, this information can become very useful if alterations are planned for the environment. So, continuing with the example, knowing the capacity that the installed system was intended for can aid the decision on whether it needs to be replaced. Knowing why a particular heating system was used in a previous project can aid the decision process for specifying heating systems in future projects.

Secondly this information is associated with the relevant aspect of comfort. Anyone reviewing a particular comfort aspect can easily review the relevant Comfort History associated with it. So, continuing the heating system example, any model that has the heating system as an input will also have the history of that heating system linked to it. This makes it easy for a person reviewing the model to access the relevant historical information.

3.3 Knowledge Storage and Access

The methodology specifies that all knowledge must be stored and accessible in a consistent and unambiguous manner, so that knowledge gained at each stage of a project is available to future project stages and future projects. The storage and access system must satisfy the BabySteps approach as specified in §1.8. It must be implementable through a number of small changes to be adoptable by the industry members. The benefit of an information environment needs to be shared between all the project members [68], therefore it must be inexpensive to use and must be compatible with the current data access and transfer.

The knowledge storage must store all the comfort related knowledge as it is created in a flexible standard format in a single central location. The knowledge that is stored is the Comfort Performances, the Comfort Ratings, the Comfort History, and all information that was required to create these, such as the Comfort Model, boundary conditions, etc. The standard format must facilitate the requirements of numerous construction users including indoor environment designers and operators. It must store both the static data and dynamic data required for a comprehensive description of the indoor environment. The static data for the ACP is the geometry of the environment and the dynamic data is the sensor measurements provided by the measurement tool. Each building in which the comfort is analysed will have a Central Knowledge Storage, as this will allow the information associated with the building to be kept with the building.

This type of Central Knowledge Storage with a standard data format facilitates the required interoperability between project stages [35], [48], [60], [78], [82]-[84] as it allows easier transfer of data between all disciplines and components. One to one integration is inefficient [34], [39], [72] as the construction industry has a variety of elements [34], [38], [46], has short-term business relationships [37], and is constantly evolving [73]. Not using a standard data format results in inefficient data re-entry [46]-[48] and the development of large monolithic software programmes [65], whereas a standard format can allow component based development. However, new data storage systems need to cater for documents in existing formats to allow easier integration with existing systems. The information is what is important and the storage system is simply a container for it [82].

3.4 Comfort Knowledge Use Scenarios

ComMet regulates the comfort knowledge so that it is available for use by whoever requires it and at any project stage. The following sections describe some more scenarios where the comfort knowledge provided by ComMet could be used.

3.4.1 Scenario – Designer

Since the Designer of the indoor environment will be experienced in the details of comfort they can use the Comfort Performances to track the success of their design. Comparing the DCP, CnCP and OCP, the Designer can identify areas to improve their designs. The ICP and RCP provide valuable design information. The FCP provides information on the benefits of proposed design changes to an existing environment. The Designer can reuse the Comfort Model if they plan to design a similar space in the future. Therefore, ComMet can allow the Designer to improve future designs by enabling them to identify areas to improve current designs and by using an existing calibrated model as a future design start point.

3.4.2 Scenario – Project Manager

Since the Project Manager may not be a comfort expert they can use the Comfort Ratings to track how the comfort of the indoor environment is progressing through the project stages. Specifically, the CR-R, CR-D, CR-C, CR-O, PSR-P, and PSR-A would be used by the Project Manager. The CR-R shows the Project Manager what is legally required and so gives him a reference point for the other Comfort Ratings. The CR-D shows how the design comfort compares to the ideal comfort. After any construction alterations the CR-C shows how the comfort now compares to the ideal comfort and the PSR-P predicts how successfully the construction process will implement the design. Once the indoor environment is operational the CR-O shows how the optimum achievable comfort conditions compare to the ideal. The CR-O is essentially a measure of the quality of the product produced by the Project Manager. The PSR-A shows how successful the project was at achieving the design intent. The PSR-A has applications in contract negotiations as a method to set required standards to be met by the project team.

One goal of the Project Manager is to have the CR-D, CR-C and the CR-O as similar as possible. In other terms the goal is to have a construction process that implements the design as accurately as possible and have a design that predicts the actual conditions as accurately as possible. Another goal of the Project Manager is to have both the value of the PSR-P and the PSR-A as close to 1 as possible. This would mean that the construction process implemented the design accurately. However, the Project Manager should ensure that any changes that need to be made during the project increase the PSR-P and PSR-A.

3.4.3 Scenario – Operation

3.4.3.1 Owner

The Owner usually requires a high level view of the building operation. Therefore, they can use the OSR and BSR to see how well the building is being operated and if it is meeting regulatory standards. They can use the CR-F and BAR to see if proposed changes to the indoor environment are beneficial.

3.4.3.2 Operator

The Operator usually requires a low level, more detailed view of the building operation. The CR-R can give them a benchmark for the legal comfort requirements. The CR-A and CR-O will show them how the environment is performing and the comfort it is capable of achieving. The OSR shows the operator how well the environment is being operated. They can use the OER as an alarm to warn them when there is a fault in the environment operation. They can use the CrSR to track the success of the model based control. They can use the Comfort History to provide information on the HVAC systems and the design intent.

The Operator may have expertise in comfort and so could use the Comfort Performances to supply appropriate information to enable them to improve comfort. The ICP, RCP, ACP, OCP, CrCP and HCP could all provide valuable information on the environment operation.

3.4.4 Summary Table

A summary of the Comfort Performances and Comfort Ratings used by typical users described in the previous sections is given in Table 3.3.

Table 3.3 – Summary of Comfort Models and Comfort Ratings used by Some Typical Building Stakeholders

	Some Typical Building Stakeholders			
	Designer	Project Manager	Owner	Operator
Comfort Performances				
ICP	✓			✓
RCP	✓			✓
DCP	✓			
CnCP	✓			
ACP				✓
CaCP	✓			
OCP	✓			✓
CrCP				✓
HCP				✓
FCP	✓			
Comfort Ratings				
CR-R		✓		✓
CR-D		✓		
CR-C		✓		
CR-A				✓

This table continues on the next page

	Some Typical Building Stakeholders			
	Designer	**Project Manager**	**Owner**	**Operator**
This table starts on the previous page				
Comfort Ratings				
CR-O		✓		✓
CR-F			✓	
PSR-P		✓		
PSR-A		✓		
OSR			✓	✓
CrSR				✓
BSR			✓	✓
OER				✓
BAR			✓	

Chapter 4

The LCMS System

4.1 Introduction

A system can be defined as *an assemblage or combination of things or parts forming a complex or unitary whole.* In this case the complex or unitary whole is the new life-cycle comfort monitoring system named LCMS. The LCMS system was developed to implement the ComMet methodology. This chapter details the LCMS system; the combination of parts used to form it; and how it satisfies all the requirements of the ComMet methodology. These requirements include:

- The specification of tools and standards to generate comfort knowledge that includes:
    - Tools and standards to generate the Comfort Performances as defined in §3.2.3;
    - A tool to calculate the Comfort Ratings as defined in §3.2.5;
    - A tool to record the Comfort History as defined in §3.2.7.
- The specification of a knowledge storage and access system as defined in §3.3;
- And compliance with the BabySteps approach as defined in §1.8.

4.2 LCMS Overview

The LCMS System, as shown in Figure 4.1, was developed to implement ComMet. It captures, stores and allows easy access to comfort knowledge as specified by ComMet. LCMS is an IT system that is a combination of six components:

- Building Standards;
- Simulation Software;
- The Egg-Whisk (Wireless Sensor) Network;
- Spreadsheet Software;

- Text Editing Software; and
- A Central Knowledge Storage and Web-Based Access.

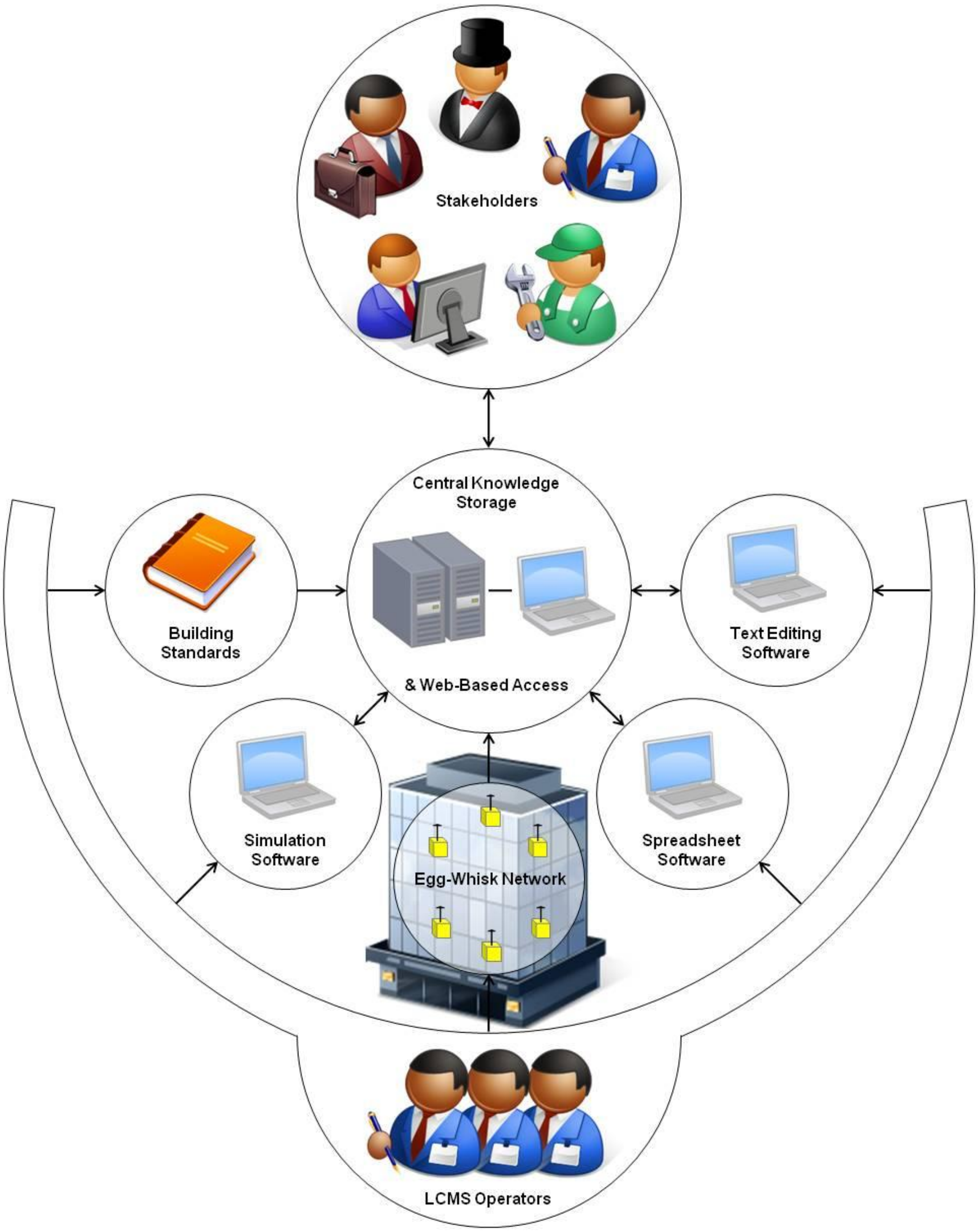

Figure 4.1 – The LCMS System

The Building Standards used in LCMS are the relevant standards for the project, which specify the ideal and required indoor environmental conditions for the indoor environment. They provide the information necessary to generate the two building standards performances specified by ComMet.

The Simulation Software is a software tool that can simulate comfort conditions in an indoor environment to the level of detail required. The simulation tool used by the LCMS system is a CFD software tool, which can simulate the comfort conditions using the relevant geometry, environmental parameters and boundary conditions. The CFD tool creates the Comfort Model.

The Egg-Whisk Network is a specially designed mobile network of wireless sensing motes that can be deployed in the indoor environment. It provides the data to calculate the Actual Comfort Performance of the ComMet methodology by measuring the main environmental conditions within that environment, such as temperature, airspeed and CO_2, to a greater detail than is currently available.

The Spreadsheet Software is a software tool that can edit and run calculations on numerical data stored in a CSV file format. This file format is used to store the measured environmental data from the Egg-Whisk Network, the Comfort Performances and the Comfort Ratings.

The Text Editing Software is a software tool that can edit text files. Text files are used to record the Comfort History.

The Central Knowledge Storage is a BIM that enables the Comfort Performances, Comfort Ratings and Comfort History created during the project to be stored in a standard format.

The web-based data access is a BIM specific website that enables access to the BIM. This means that it can be used to transfer comfort knowledge to and from the BIM. This gives all project stakeholders access to all the comfort knowledge that is available.

LCMS is specifically designed to satisfy the theory of BabySteps as it can be implemented into the industry through a number of small changes.

Table 4.1 lists a summary of the ComMet requirements and the LCMS component that fulfils each one. §4.3 describes each of the LCMS components in detail and how they implement the ComMet methodology.

Table 4.1 – Summary of ComMet Requirements and the Corresponding LCMS Components

ComMet Requirements	LCMS Component
Comfort Knowledge	
Comfort Performances	
• Building Standards Performances	• Building Standards • Spreadsheet Software
• Simulated Performances	• Simulation Software • Spreadsheet Software
• Measured Performance	• Egg-Whisk Network • Spreadsheet Software
Comfort Ratings	• Spreadsheet Software
Comfort History	• Text Editing Software
Knowledge Storage & Access	
Storage System	Central Knowledge Storage
Access System	Web-Based Access
BabySteps	All Components comply with BabySteps

4.3 LCMS Components

4.3.1 Building Standards

The Building Standards used in LCMS are the relevant standards for the project, which specify the ideal and required conditions for the indoor environment. Some examples include the CIBSE Design Guides[14], ASHRAE

[14] www.cibse.org

Standards [15], and the ISO Standards [16]. They provide the information necessary to create the Ideal Comfort Performance and the Required Comfort Performance, which are the two building standards performances specified by ComMet.

4.3.1.1 BabySteps and Building Standards

Building Standards satisfy BabySteps as they are already being used in the industry and do not need to be newly implemented.

4.3.2 Simulation Software

The Simulation Software is a CFD software tool, which can effectively model and simulate the comfort conditions of the indoor environment using the relevant geometry, environmental parameters, and boundary conditions. Using the inputs as specified in §3.2.3, the CFD tool creates the Comfort Model, which generates the seven simulated Comfort Performances:

- Design Comfort Performance;
- Construction Comfort Performance;
- Calibrated Comfort Performance;
- Optimum Comfort Performance;
- Control Comfort Performance;
- Historical Comfort Performance; and
- Future Comfort Performance.

4.3.2.1 BabySteps and Simulation Software

CFD is already being used in the industry for fire safety design and indoor environment design to a lesser extent. It is compatible with the existing design systems and has the potential to be compatible with other BLC systems. Therefore, it satisfies BabySteps as it does not need to be newly implemented into the industry.

4.3.2.2 Technical Details of CFD

CFD is the application of numerical methods to the solution of discrete models of the constituent equations of fluid mechanics [92]. It is used in numerous disciplines from the flow of air across an airplane wing to the flow

[15] www.ashrae.com
[16] www.iso.org

of blood within the human body. It can be applied in many areas in building design including fire safety, pollutant containment, and thermal conditions. CFD is a highly accurate tool, which could, and should, supply very detailed information of the indoor environment during all stages of the building project.

However, CFD is under-utilised in the building sector partly due to a lack of calibration data needed to verify its accuracy. This results in un-calibrated CFD models providing little more than 'pretty pictures' and a general, unverified understanding of the indoor environment. As previously described in §1.5.2, enabling building specific CFD models to be calibrated will be a big step towards making CFD an effective tool for building design and operation. In fact, ASHRAE deems it "*essential*" that CFD models can be calibrated using measured data in order to make CFD a design and analysis tool for indoor environments [93].

The under-utilisation of CFD in the industry means there is little industry specific expert knowledge and software, which makes CFD expensive, complex and even less advantageous to the construction industry.

In this respect, ComMet and CFD are mutually beneficial to each other. CFD provides ComMet with the required simulation models and ComMet provides CFD with the calibration data necessary to validate its models and make it more useful for the industry. Table 4.2 compares Un-Validated CFD and Validated CFD under the Diffusion of Innovation Criteria, as described in §1.7, and shows the advantages Validated CFD have in getting adopted by the industry.

Table 4.2 - Comparison of Un-Validated CFD and Validated CFD under the Diffusion of Innovation Criteria

Diffusion of Innovation Criteria	Un-Validated CFD	Validated CFD
Relative Advantage	Two small advantages are: It produces 'Pretty Pictures' which are a useful marketing tool; and it gives a general, un-validated understanding of the environment. Because there are few advantages to Un-Validated CFD it is under-utilised in the industry. This in turn means there is little industry specific expertise and software which makes CFD expensive, complex and even less advantageous.	The advantages of Validated CFD are: improved designs; improved operation; detailed, validated understanding of the environment; and the production of 'Pretty Pictures'.
Complexity	Un-Validated CFD is complex.	Validated CFD is complex but improved understanding is gained from the calibration data
This table continues on the next page.		

Diffusion of Innovation Criteria	Un- Validated CFD	Validated CFD
This table starts on the previous page.		
Compatibility	Un-Validated CFD is compatible with the current design systems and so has the potential to be compatible with other BLC systems.	Validated CFD is compatible with the current design systems and so has the potential to be compatible with other BLC systems.
Trial-ability	Trials of Un-Validated CFD in real world situations are possible but usually not beneficial because the results of the trials are un-validated.	Trials of Validated CFD in real world situations are possible and beneficial.
Observe-ability	Demonstrations of Un-Validated CFD in real world situations are possible but usually not beneficial because the results of the demonstrations are un-validated.	Demonstrations of Validated CFD in real world situations are possible and beneficial.

4.3.2.3 CFD Model Generation Procedure

CFD is used to create the Comfort Model for LCMS. There are 6 main steps in the generation of a CFD model.

Step 1: Geometric information

The geometry of the indoor environment space is created in the CFD software.

Step 2: Addition of Boundary Conditions, and Mesh and CFD Parameters

The relevant boundary conditions and environment parameters such as surface temperatures, flow rate and temperature from air diffusers, occupants, etc., are inputted.

Step 3: Mesh Generation

The first step in the analysis is the mesh generation. The mesh generator uses the mesh parameters, such as the maximum size of the mesh cell at specified locations in the space, and the geometry to generate a finite element mesh of the environment. The mesh is then analysed for accuracy by the user.

Step 4: CFD Solver

The mesh file, along with boundary conditions, such as flow rates, and the CFD solver parameters, such as flow regime, is mapped to the CFD solver. The solver then produces a results file.

Step 5: Grid Independence

Steps 3 & 4 are repeated with finer and finer mesh sizes until grid independence is reached. Grid independence is achieved when a reduction in the cell size of the mesh does not produce a change in the results.

Step 6: CFD Model Calibration (if the ACP is available)

Calibration can be defined as *the process of adjusting numerical or physical modelling parameters in the computational model for the purpose of improving agreement with experimental data* [94]. Firstly, a set of validation criteria are defined. Validation criteria define the acceptable difference between the simulated results and the actual measured data from the Egg-Whisk Network. If these criteria are not met then a sensitivity analysis is carried out. This analysis identifies the most significant input model parameters. Along with repeating Steps 3 & 4, these parameters are repeatedly and systematically adjusted until the validation criteria are met.

Step 7: Storage of CFD Model

All the data generated during this analysis is stored back in the Central Data Storage.

4.3.3 Egg-Whisk Network

The Egg-Whisk Network is a wireless sensor network (WSN) developed by this research. It is comprised of a number of wireless Egg-Whisk Motes connected by way of a dedicated 'Star Network' to a base computer, as shown in Figure 4.2. These motes record the environmental data from the indoor environment required to generate the ACP and send it back to the base computer. This base computer then accesses the BIM through the website and stores the data, where it can later be accessed in order to create the ACP using the spreadsheet software. The Egg-Whisk Network has also been used to supply data to a project developing a formal scientific methodology for developing calibrated CFD models of indoor spaces [90].

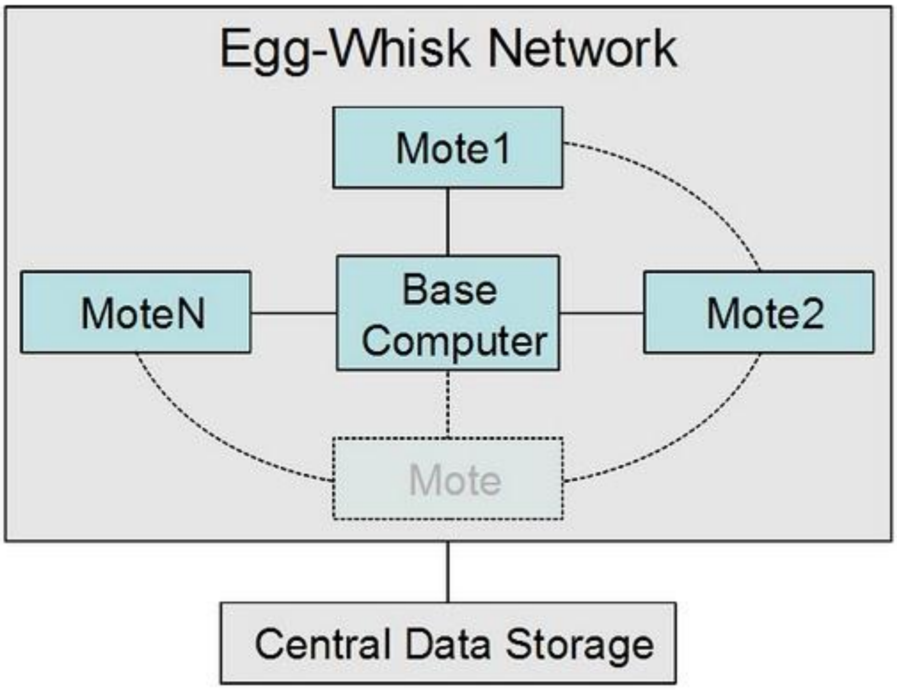

Figure 4.2 – Egg-Whisk Network Schematic

The Egg-Whisk Mote, as shown in Figure 4.3, is an environmental sensing micro-system designed to obtain a comprehensive record of the environmental conditions at a particular point within an indoor space by way of a number of on-board sensors. The mote measures airspeed in ‘m/s’, CO_2 in ‘ppm’, temperature in ‘°C’ and relative humidity in ‘%’. These sensor components were chosen to enable the calculation of comfort of the indoor environment as confirmed by Kosonan & Tan [12], Lan & Lian [95] and CIBSE [14]. Due to resource limitations, a radiant sensor was initially not installed on the mote and instead the radiant temperature of the space, which is required for the comfort calculation, is currently obtained from an independent portable radiant sensor. The Egg-Whisk Network can contain many of these motes and can, therefore, simultaneously collect detailed data from multiple locations within an indoor environment.

Figure 4.3 – The Egg-Whisk Mote

A WSN was chosen for this system because currently they are promoted and, in some cases adopted, as a method to monitor indoor environments [50], [95], [96]. WSN's are ideal for a mobile system that is used in existing operational indoor environments as they are:

- Cheap – Installation of wiring represents 20% to 80% of the cost of a sensor point in an HVAC system [97];
- Easy to install – Installation of wireless sensors consists only of placing the sensor where it is required. It is not restricted by location of power sources or data communication points [50];
- Flexible – Again because of lack of restrictions, wireless sensors are easy to relocate [50];
- Extendible – Wireless sensor communication technology allows new sensors to be automatically added to a WSN [50];
- Compact – The Multi-Sensor Layer of the Egg-Whisk Mote which contains seven independent sensors is only 25mm x 25mm x 5mm. This is described in detail in §4.3.3.2; and
- Portable – The WSN's compactness, lack of cabling, and ability to automatically establish a communication network, makes it highly portable.

4.3.3.1 BabySteps and the Egg-Whisk Network

The Egg-Whisk Network satisfies BabySteps because wired sensors are already employed in environmental control in many buildings and so incorporating wireless sensors in the future, when the technology is more robust, will not require a significant change.

4.3.3.2 Technical Details of the Egg-Whisk Network

The Egg-Whisk technology is based around the Tyndall modular WSN prototyping system [96], with application specific sensor layers developed for indoor environment scenarios. The Egg-Whisk mote consists of a three layer modular stack. The base layer contains the battery pack, the airflow sensor and the CO_2 sensor. The mote is powered by two 740mA/hr re-chargeable Li-ion batteries. This means low power consumption sensors and implementation have been utilised, where possible. However, this limited battery power does result in a short recording time. Air flow sensing is accomplished using an integrated hot bulb type air flow sensor from Dantec [98] with the capability to measure indoor convection air flow speeds with a range of 0.05 - 1m/s with a sensitivity of 0.01m/s. The mote contains an infrared CO_2 gas sensor [99], with a measurement range from 0 - 2000 ppm and sensitivity of ± 20 ppm.

This highly integrated sensing solution can be further enhanced by plugging in the modular Multi-Sensor Layer, as shown in Figure 4.4, resulting in a flexible solution available for rapid deployment [100]. The Multi-Sensor Layer is comprised of a thermistor to measure changes in temperature, a relative humidity sensor, a light dependent resistor to measure ambient lighting levels, a three axis accelerometer to monitor movement and a microphone to detect sound.

The Transceiver Layer [101], as shown in Figure 4.5, was developed to provide RF communications capability between sensor motes. The layer incorporates a micro-controller driving a transceiver operating in the 2.4GHz ISM band. The embedded micro-controller is the Atmel AVR ATMega128L [102], an 8-bit micro-controller with 128 Kbytes in-system programmable flash, allowing development of custom communication protocols and sensor interface solutions. The transceiver used is a 2.4GHz ISM band transceiver from Nordic VLSI [103], the nRF2401, capable of transmitting and receiving data in high data rate bursts to implement reduced power consumption functionality. The resources are not available to compile a full technical data sheet of the Egg-Whisk Network however more technical details are in Annex D.

The Egg-Whisk Network was developed by the Tyndall National Institute Ireland [104] and the IRUSE Group in the Department of Civil Engineering, National University of Ireland, Cork and Galway [105].

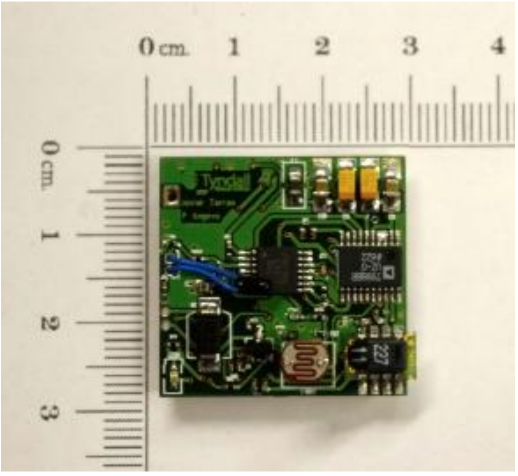

Figure 4.4 – Multi-Sensor Layer

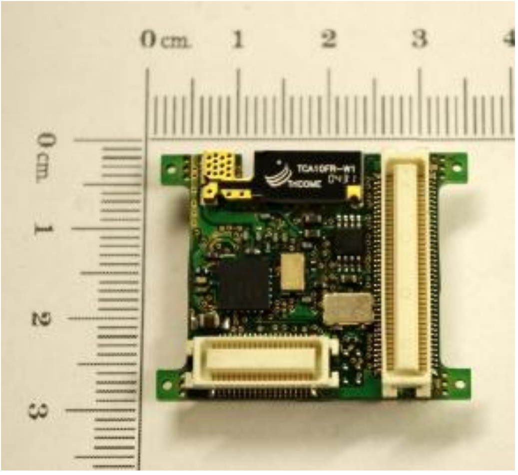

Figure 4.5 – Transceiver Layer

4.3.4 Spreadsheet Software

The Spreadsheet Software is a software tool that can edit and run calculations on numerical data stored in a CSV file. This file format is used to store the measured environmental data from the Egg-Whisk Network, the Comfort Performances, and the Comfort Ratings.

The Spreadsheet Software is used to generate the ACP and the seven simulated performances. It generates the ACP using the measured data from the Egg-Whisk Network, which is stored in the BIM. It generates the simulated performances using the environmental values from the Comfort Model. It uses an iterative process to calculate the result of the PPD equation as defined in Annex C. The PPD and the CO_2 value can then be combined to generate the Comfort Performances and these are stored in CSV format. Storing the Comfort Performances in CSV format allows them to be easily used to create the Comfort Ratings.

4.3.4.1 BabySteps and Spreadsheet Software

Spreadsheet Software is used throughout the construction industry and the BLC for numerical calculation and storage purposes. It satisfies BabySteps as it is a commonly used tool and does not need to be newly implemented into the industry.

4.3.5 Text Editing Software

The Text Editing Software is a software tool that can create and edit text files. Text files are used to record and store the Comfort History in the BIM.

4.3.5.1 BabySteps and Text Editing Software

Text Editing Software is used throughout the construction industry and the BLC for information storage purposes. It satisfies BabySteps as it is a commonly used tool and does not need to be newly implemented into the industry.

4.3.6 Central Knowledge Storage & Web-Based Access

The Central Knowledge Storage, as shown in Figure 4.6, is a BIM and is used to store all the comfort related knowledge in a standard format as specified by ComMet. The format chosen for this research is the industry foundation classes (IFC) [55]. IFC is designed to facilitate the requirements of numerous construction users, including indoor environment designers and operators. The BIM will store both the static data and dynamic data required for a comprehensive description of the indoor environment. For example, the dynamic data for the ACP will be the sensor measurements provided by the Egg-Whisk Network. A BIM will be created for each building in which a space is analysed as this will allow the information associated with the building to be kept with the building.

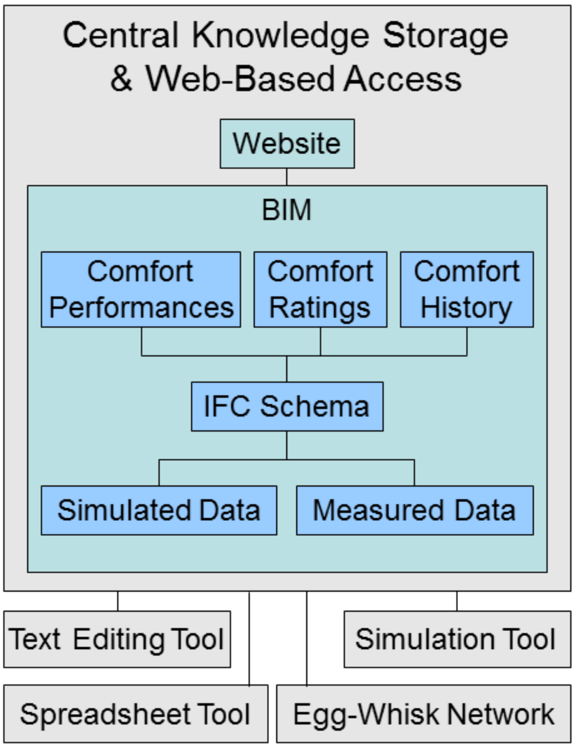

Figure 4.6 – Central Knowledge Storage & Web-Based Access Schematic

This type of Central Knowledge Storage with a standard data format facilitates the required interoperability for integrating the BLC stages more meaningfully [35], [48], [84] as it allows easier transfer of data between all elements of the construction industry. One to one integration is inefficient [34], [39], [72] as the construction industry:

- Has a variety of elements [34], [38], [46];
- Has short-term business relationships [37]; and
- Is constantly evolving [73].

Not using a standard data format results in inefficient data re-entry [46], [47] and the development of large monolithic software programmes [65], whereas a standard format can allow component based development. However, BIM systems need to cater for documents in existing formats to allow easier integration with existing systems. The information is what is important and the BIM is simply a container for it [82].

IFC was chosen as the standard format for this research as it has the greatest potential and it is regarded by some to be the future of BIM [46], [59], [75]. The benefits of IFC are:

- It is object orientated so it equates well with the real world [34];
- It allows the storage of data for a building, such as geometry, materials, etc., throughout its lifecycle;
- It is extendable through its property set functionality and is flexible enough to be developed for other engineering areas [75]; and
- It is an open-source international standard allowing others to easily and speedily reuse data [85].

The IFC schema is not currently able to optimally support all components of LCMS. For example, with respect to CFD, geometric and HVAC entities are supported in IFC but mesh and CFD entities do not currently exist and will need to be developed as IFC entities. §6.3.2 discusses this in more detail. However, the IFC schema provides a method of creating properties for non-existing entities allowing the scope of the schema to be expanded to incorporate new information such as Comfort Performances, Comfort Ratings and Comfort History.

IFC is not perfect. It is still evolving. But as Kimon Onuma (CEO of Onuma Inc.) wrote: *"Just like the Internet that is never complete, if you wait for standards to be 'finished' you will watch the train leave the station. All are welcome aboard, the train is moving fast."* [82].

Some test-case IFC systems have been developed [58], [75] but there has been limited commercial development as the larger commercial companies only provide limited support for IFC e.g. AutoDesk and Bentley [46]. Since they provide the most prominent BIM solutions, IFC is not making it to the industry [75]. This is understandable as an open-source standard data format encourages competition. Still, adoption of an alternative commercial de-facto standard is unlikely as there are too many big commercial software providers in the sector.

Having web-based access to the BIM adds benefits to the system. It reduces costs for the user by reducing hardware and software requirements [48]. It facilitates the current trend towards mobile working [84], web-based data transfer [106] and on-site data access [48].

4.3.6.1 BabySteps and the Central Knowledge Storage & Web-Based Access

A simplified, but extensible, BIM was designed for this research, which currently just focuses on the management of the comfort knowledge for the indoor environment. This BIM satisfies BabySteps because Central Knowledge Storage is already being used in the industry through the use of EDM, as described in §1.6, so incorporating a simplified BIM with a standard format just to store comfort knowledge will not require a significant change.

The web-based data access was chosen as most users are familiar with web-based applications [72] and the construction sector has already acknowledged that one of the main benefits of IT is the access it provides to information [60]. It satisfies BabySteps as it is a commonly used and respected tool and does not need to be newly implemented into the industry.

4.3.6.2 Technical Details of the Central Knowledge Storage & Web-Based Access

BIM technologies such as the Eurostep[17] or the EDM Model Server[18] were investigated for this research. However, these comprehensive systems were prohibitively expensive for a non-commercial organisation. Against this backdrop, use of Microsoft's Visual Web Developer website development tool[19] in conjunction with the freeware IFC development toolbox, IFCsvr ActiveX component[20] was used.

The two main purposes of this BIM are:

1. To store an IFC file with building geometry and sensor definitions, which correspond to the locations where the Comfort Performances are created for; and
2. To enable comfort knowledge sources to be linked to specific sensor objects within the BIM.

[17] www.eurostep.com
[18] www.epmtech.jotne.com
[19] www.microsoft.com/express/Web
[20] www.secom.co.jp/isl/e2

A simple website was developed that could access an IFC file stored in a file directory on a computer, load the file into the BIM and identify all sensor definitions from the file. The website creates the link between the sensor definitions within the BIM and:

- The measured environmental data from the Egg-Whisk Network;
- The Comfort Performances;
- The Comfort Ratings; and
- The Comfort History.

Each object stored in IFC has a unique identifier. By maintaining this identifier with the stored knowledge, it becomes possible to create a one to many relationship with the sensor and the instances of related comfort knowledge. In this way, the website operator may choose a particular BIM object and associate it with several relevant knowledge sources.

4.4 LCMS Operators

All project stakeholders will be potential users of LCMS during the project and these will include the client, project manager, architect, designer, construction contractor, and operator. These users will use the six components of the LCMS system, as described in §4.3 to capture, store and access the Comfort Performances, Comfort Ratings, and Comfort History, as specified by ComMet, to enable comfort knowledge re-use in future project stages and future projects.

4.5 Comfort Knowledge Use Scenarios

4.5.1 Scenario – Comfort Rating - Actual

§3.2.2.1.1 described a typical scenario of how the CR-A could be used. Now that LCMS has been defined, more detail can be added to that scenario as shown in Figure 4.7. Firstly the Knowledge-Base is implemented using the Central Knowledge Storage and Web-Based Access of the LCMS system as defined in §4.3.6. As previously described the CR-A is created by the LCMS Operators using the various tools of LCMS and then the CR-A is stored in the Central Knowledge Storage where it is available to the stakeholders through the Web-Based Access. The Web-Based Access is the tool that is used to automatically inform the stakeholders if the CR-A drops to an unacceptable level.

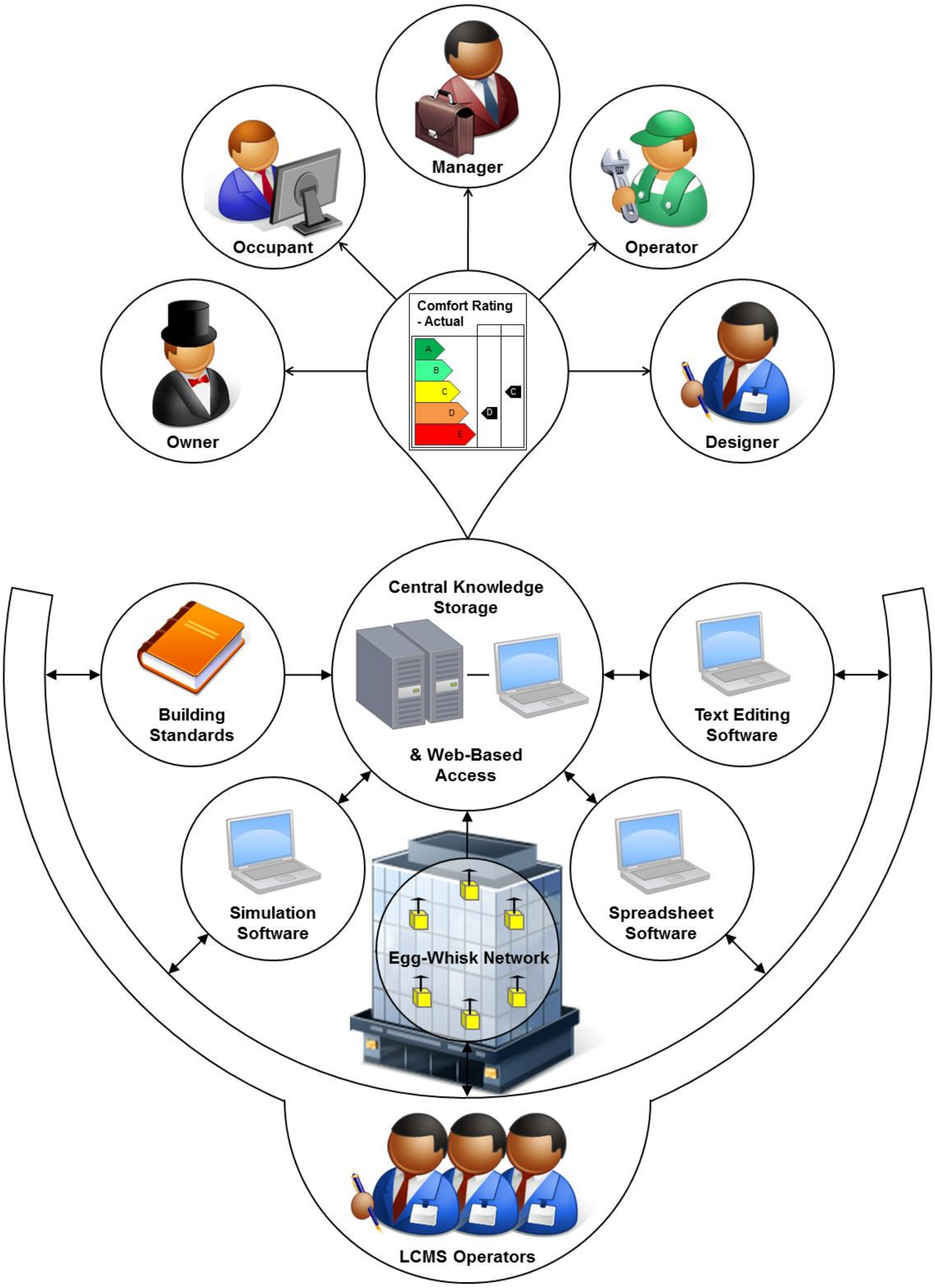

Figure 4.7 – CR-A Use Scenario

Chapter 5

Test-Case

5.1 Specification

This test-case has three consecutive goals:

1. To test the operation of LCMS;
2. To show how LCMS implements ComMet;
3. And to show that ComMet proves the hypothesis that states that the occupant comfort in the indoor environment can be improved if the comfort knowledge gained at each stage of a building project is captured, stored and made available to future project stages and future projects in a consistent and unambiguous manner.

An existing office room in University College Cork's Environmental Research Institute[21] was chosen as the test-case for the new system. The room is heated using under-floor heating and fan assisted radiators. The ventilation is manual natural ventilation through the windows. The room is a typical operational office room where the new LCMS system would be used. It was expected that the results would give an improved understanding of the room and identify areas for improved operation. The geometry was created using IFC compatible software, a graphical representation of which is shown in Figure 5.1. This geometry was then stored into the BIM.

[21] www.ucc.ie/en/eri

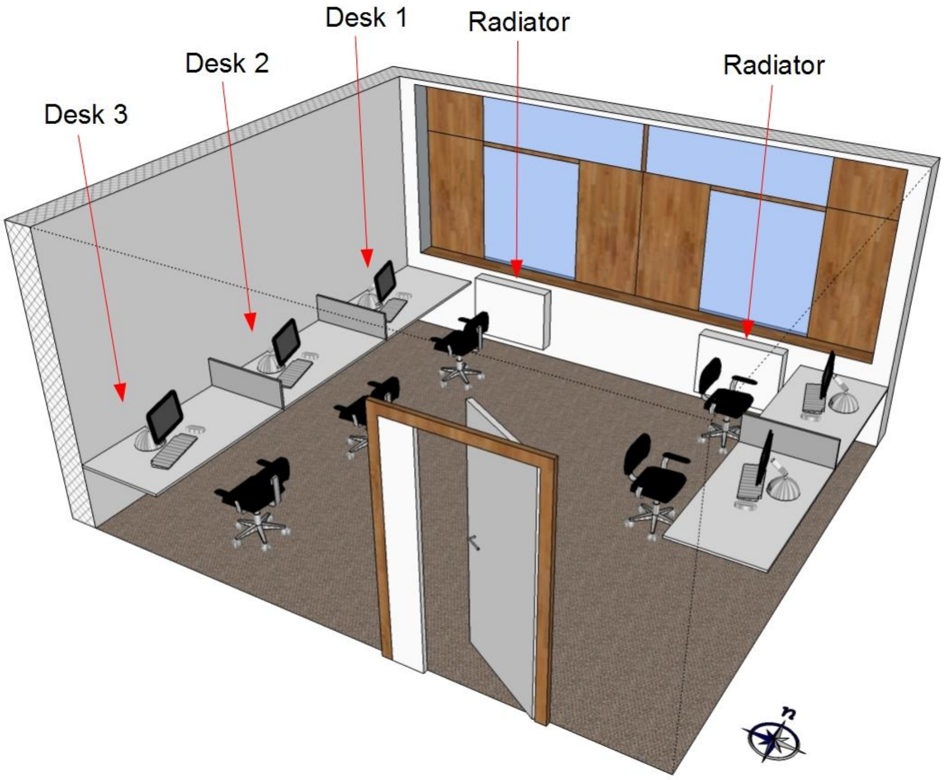

Figure 5.1 – Test-Case Room

5.2 Project Procedure

The procedure in which the Comfort Performances, Comfort Ratings, and Comfort History are produced for this test-case is shown in Figure 5.2. The Comfort Ratings are produced once the required Comfort Performances are produced so, for example, the Comfort Rating – Design is produced once the Ideal Comfort Performance and the Design Comfort Performance are produced. More details on the data used to create the Comfort Performances are included in Annex E.

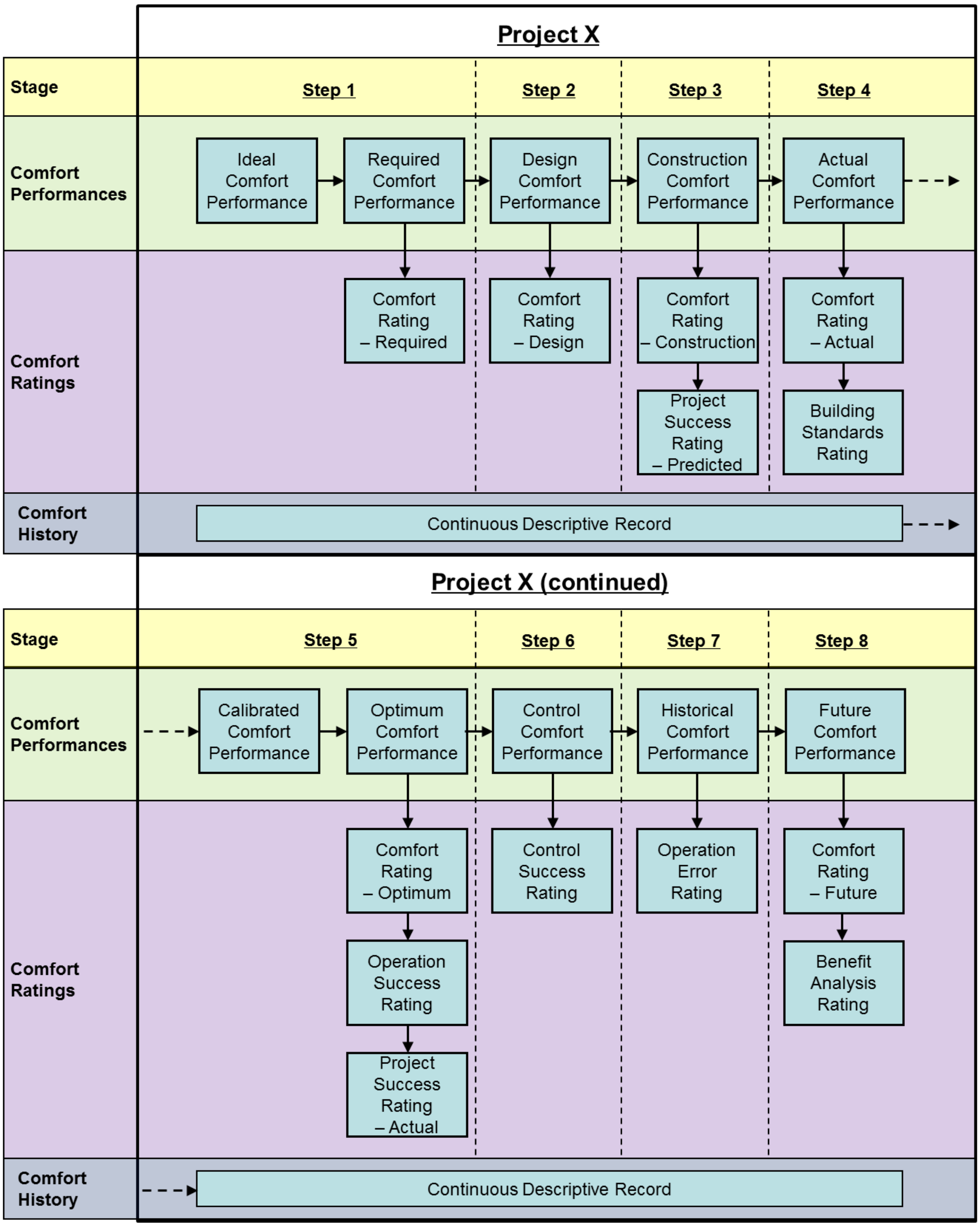

Figure 5.2 – Test-Case Production Procedure for Comfort Performances, Comfort Ratings and Comfort History

5.2.1 Step 1

5.2.1.1 Ideal Comfort Performance (ICP)

The CIBSE design guides state that the ideal PPD for an office room is 5% and that the ideal CO_2 is 750ppm. The CO_2 value corresponds to an indoor air quality classification of IDA 1, which is the highest classification for indoor air and it allows for a CO_2 rise of 350ppm above the outdoor air value. Ideally, indoor concentration of CO_2 would be closer to the outdoor concentration of between 300 – 400ppm, if the space is adequately ventilated. However, in order to keep in line with the current design standards the ICP for this test-case is (5%, 750ppm).

5.2.2 Step 2

5.2.2.1 Required Comfort Model (RCM)

The CIBSE design guides state that the required PPD value for an office is 13.4%. No specific guidance is given for required CO_2 level in an office room. CIBSE states that an air supply rate of 10l/s per person is required for an office room. This value corresponds to an air quality classification of IDA 3, which in turn corresponds to a CO_2 value of 1200ppm. Therefore, the RCP for this example is (13.4%, 1200ppm).

5.2.2.2 Comfort Rating – Required (CR-R)

The CR-R was calculated as (0.37PPD, 0.63CO_2). This compares the required performance to the ideal performance. Using the Comfort Rating Bands this rating can also be expressed as (D [PPD], B [CO_2]) showing that the required thermal conditions are in band D and the air quality is in band B.

5.2.3 Step 3

5.2.3.1 General Comfort Model Details

The purpose of the test-case was to demonstrate an implementation of LCMS. Over fifty simulations were performed in order to achieve this. Therefore, in order to complete the test-case in a reasonable time a runtime limit of three hours was put on the simulation of the Comfort Model. This runtime consisted of a one hour model steady-state simulation to establish a stable model, and a two hour transient simulation to model the room for the test-case period. The model was simulated for each of the simulated Comfort Performances, and many versions of the simulation needed to be performed in some cases. The Future Comfort Performance required ten simulations to identify a system that would improve the comfort conditions in the room. The time to perform the various aspects of LCMS can be reduced by making upgrades, such as using automatic model calibration and optimisation techniques, and improving simulation hardware specifications.

The CFD parameters, such as the mesh grid size, steady-state runtime length, transient time-step, and iterations per time-step, were chosen to give reasonable model accuracy within required runtime. The results of the calibrated Comfort Model show this, as they are within 2.7% of the actual comfort conditions. A summary of the CFD parameters are given in Annex E, and the full parameter details are given in the CFD simulation files in the accompanying disc.

5.2.3.2 Design Comfort Performance (DCP)

Since no Comfort Model existed for the room a hypothetical Comfort Model was developed. There was inadequate data available on the design of the building so some assumptions were made in order to create the Comfort Model. The following are some of the main pieces of information used to generate the Comfort Model:

- The design temperature for the room is 22°C;
- There is no automatic control for CO_2 or humidity and the manually operated windows in the room would not be opened during winter weather conditions due to the cold external temperature;
- The actual geometry was used as the design geometry data;
- The mean external temperature is 4°C. It was the external temperature from the day the ACM was generated;
- Air leakage to and from the room is negligible.

The CFD software package CFX from Ansys[22] was used to create the Comfort Model and a DCP of (7.9%, 5,423ppm) was generated.

5.2.3.2.1 Analysis

The DCP shows that designing the room for just a prescribed temperature of 22°C provides very poor comfort. The thermal conditions parameter of the comfort is good and well within the required standards but the air quality is poor. This is expected considering that there is no automatic air quality control installed in the room. However, the assumption that the air leakage to

[22] www.ansys.com

and from the room is negligible is based on the presumption of perfectly air-tight construction, which is generally not the case. This also contributes to the very high CO_2 value.

5.2.3.3 Comfort Rating – Design (CR-D)

The CR-D was calculated as (0.63PPD, 0.14CO_2) or (B [PPD], E [CO_2]). This compares the design performance to the ideal performance. This means that the design is close to the ideal with respect to thermal conditions but is very far away with respect to air quality.

5.2.4 Step 4

5.2.4.1 Construction Comfort Performance (CnCP)

Since no CnCP existed for the room a hypothetical CnCP was also generated. There was inadequate data available on the construction of the building so the data used to generate the DCM was used to generate the CnCP. Some obvious construction changes or defects were included in the model, such as unsealed gaps around piping and ducting passing through walls. The Comfort Model generated a CnCP of (10.1%, 3,392ppm).

5.2.4.1.1 Analysis

The CnCP shows that the construction changes had a significant effect on the comfort of the room. The thermal conditions parameter was reduced but more obvious is the significant improvement in the air quality. This is due to the improved air exchange in the room due to the unsealed gaps around piping and ducting passing through walls.

5.2.4.2 Comfort Rating – Construction (CR-C)

The CR-C was calculated as (0.5PPD, 0.22CO_2) or (C [PPD], D [CO_2]). This compares the construction performance to the ideal performance. This rating shows that the changes made during construction affected both parameters of the Comfort Performance by lowering the thermal conditions into band C and raising the air quality into band D.

5.2.4.3 Project Success Rating – Predicted (PSR-P)

The PSR-P was calculated as (0.79PPD, 1.6CO_2). This compares the construction performance to the design performance. This rating predicts that the construction will not achieve the design comfort with respect to thermal conditions but will improve on the design with respect to air quality.

5.2.5 Step 5

5.2.5.1 Actual Comfort Performance (ACP)

The ACP was created using the Egg-Whisk Network. The network was set-up with motes located at Desk 1, 2, & 3 and was operated on Wednesday the 26th of January 2011, from 10:00 to 18:00. Note that the choice of day for the experiment is immaterial as ComMet is seasonally independent. This day was chosen for the test-case period as it was a typical eight hour day. The air temperature, humidity, radiant temperature, air velocity, and CO_2, were recorded at approximately 2.5 second intervals, giving over 150,000 measurements for the test-case. The mean external temperature for the day was 4°C. There were three occupants in the room for the duration of the day, with an extra seven people in the room for a meeting between 11.00 and 13.00. This gives an average of five occupants for the full day.

A graphical representation of the ACP results throughout the day are shown in Figure 5.3 – Figure 5.5.

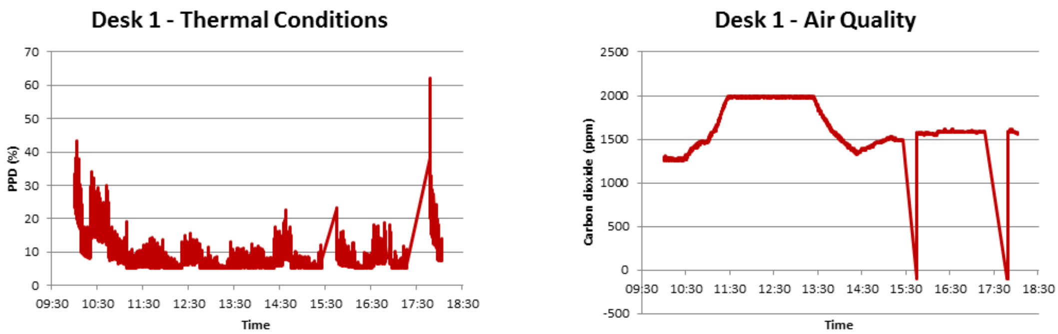

Figure 5.3 – Desk 1 Comfort Results

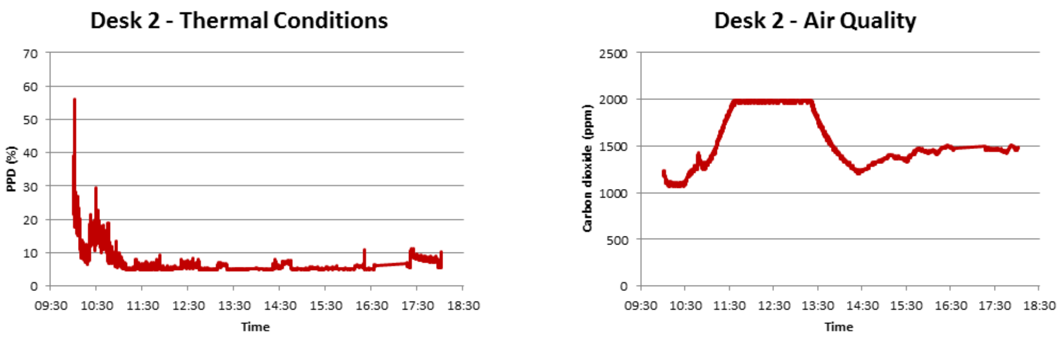

Figure 5.4 – Desk 2 Comfort Results

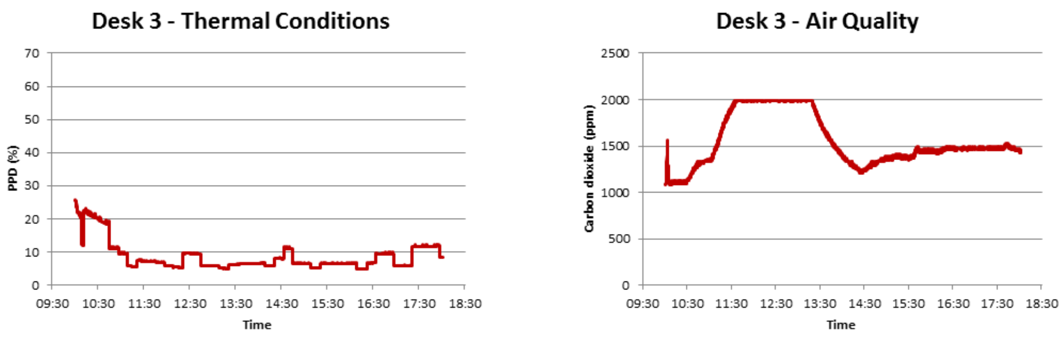

Figure 5.5 – Desk 3 Comfort Results

The average of the instantaneous ACP s was taken as the ACP for the day. The following are the daily ACP s for each desk:

- Desk 1 ACP = (8.5%, 1651ppm);
- Desk 2 ACP = (6.6%, 1551ppm);
- Desk 3 ACP = (8.7%, 1552ppm).

The average of the three desk ACP's was taken as the room ACP. Therefore, the LG04 ACP was measured as (7.9%, 1585ppm). If there were more Egg-Whisk Motes available all five desks would have been monitored and this would have given a complete room ACP.

5.2.5.1.1 Analysis

Figure 5.3 results shows two outlying values at times of approximately 15:45 and 17:45. This was caused by a malfunction in the mote, whereby data transmission stopped for approximately 20 minutes and 30 minutes respectively. This shows that the operation of the hardware has a large impact on the quality of the data received and identifies the requirement to use robust data validation techniques to ensure data quality.

The CO_2 value plateaus from approximately 11.30 to 13.30. This was because the CO_2 sensor on the Egg-Whisk mote has a range upper limit of 2000ppm. This means that the CO_2 value in the ACP is lower than what was actually the case.

The level of measurement detail was not necessary, and the time interval could be lengthened. The most suitable time interval would be decided based on an analysis of the hardware capabilities combined with the level of detail required to give an appropriate accuracy.

5.2.5.2 Comfort Rating – Actual (CR-A)

The CR-A was calculated as (0.63PPD, 0.47CO_2) or (B [PPD], C [CO_2]). This compares the actual performance to the ideal performance.

5.2.5.3 Building Standards Rating (BSR)

The BSR was calculated as (1.7PPD, 0.76CO_2). This compares the actual performance to the required performance. This rating shows that the actual comfort exceeds the required with respect to the thermal conditions but is less than the required with respect to air quality. This shows that the actual comfort does not comply with the requirements specified in the building standards, which are the CIBSE design guides in this test-case.

5.2.6 Step 6

5.2.6.1 Calibrated Comfort Performance (CaCP)

The Comfort Model was then calibrated. The actual geometry, the weather data from the day the measurement was carried out, and the occupant numbers were used as the input parameters for the Comfort Model, which was then calibrated using the ACP. A CaCP of (7.7%, 1,628ppm) was generated.

5.2.6.1.1 Analysis

The CaCP is within 2.3% for the thermal conditions and 2.7% for air quality. This model, therefore, gives a good representation of actual comfort conditions in the room.

5.2.7 Step 7

5.2.7.1 Optimum Comfort Performance (OCP)

The Comfort Model was then used to generate the OCP. The only adjustable environmental parameter for this model was the heating system. The parameters of this heating system were adjusted to produce an OCP of (6.0%, 1,484ppm).

5.2.7.1.1 Analysis

The identified optimum control strategy that produced this performance required that the output temperature of the under-floor heating be increased by 1°C. This increase in temperature resulted in an increase in the PPD of 1.9%, which, as described in §1.4.2, approximately equates to an increase in productivity of 0.95%. If that improved comfort was maintained for a full year that would equate to a gain of €1,950 to the employer for the room's five occupants. This value can be increased further by taking into account the improvement in air quality of 101ppm.

Figure 5.6 shows an image of a CO_2 concentration contour plot in the room for the OCP. The occupants are represented by the grey objects. It is clear to see that the highest concentrations of CO_2 are located at the occupied desk space. The lowest concentrations of CO_2 are at ceiling height. These are the locations of the unsealed gaps around piping and ducting passing through walls. Most importantly though, it can be seen that if the measurements of CO_2 were taken at an 'average' mid-point in the room instead of at the occupied desk space as achieved by the Egg-Whisk Network the values for CO_2 would be misrepresentative of the values actually experienced by the occupants.

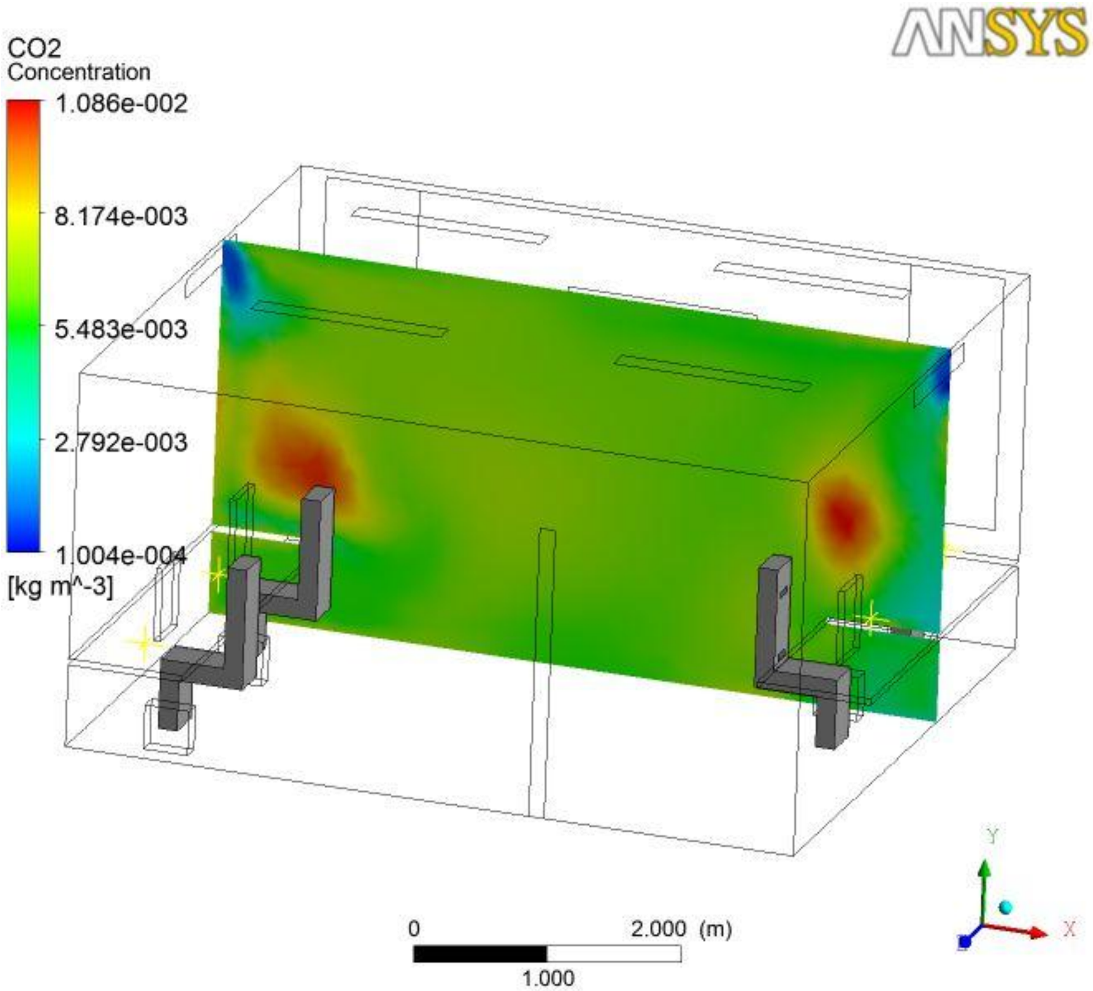

Figure 5.6 – Image of CO_2 Concentration Contour Plot in the Room

5.2.7.2 Comfort Rating – Optimum (CR-O)

The CR-O was calculated as (0.83PPD, 0.51CO_2) or (A [PPD], C [CO_2]). This compares the optimum to the ideal. This rating shows that if the optimum control strategy was used the comfort level in the room could be raised into band A for thermal conditions but would remain in band C for air quality.

5.2.7.3 Operation Success Rating (OSR)

The OSR was calculated as (0.76PPD, 0.94CO_2) or (B [PPD], A [CO_2]). This compares the actual to the optimum. This rating shows that the operation of the room with respect to comfort is in band B for thermal conditions and in band A for air quality.

5.2.7.4 Project Success Rating – Actual (PSR-A)

The PSR-A was calculated as (1.32PPD, 3.65CO_2). This compares the optimum to the design. This rating shows that the project over achieved the level of comfort in the room predicted by the design. This can be explained because the DCP did not include the air leakage affects in the room which improved the air exchange rate and so improved the air quality and the thermal conditions.

5.2.8 Step 8

5.2.8.1 Control Comfort Performance (CrCP)

Since it was not possible to adjust the control strategy for this test-case project, a hypothetical CrCP was generated. It was assumed that the control strategy was chosen for a predicted higher outside temperature of 6°C. Using this information the CrCP was calculated as (6.8%, 1,515ppm).

5.2.8.2 Control Success Rating (CrSR)

The CrSR was calculated as (0.86PPD, 0.96CO_2). This compares the actual to the control. This rating shows that the Control Comfort Performance predicted the comfort levels quite accurately.

5.2.9 Step 9

5.2.9.1 Historical Comfort Performance (HCP)

The HCP was then calculated. The Comfort Model was adjusted to include the actual control strategy used and the actual weather conditions. The HCP was calculated as (7.7%, 1,628ppm).

5.2.9.1.1 Operation Error Rating (OER)

The OER was calculated as (0.98PPD, 1.03CO_2). This compares the actual to the historical. This rating shows that there is no error in the operation as the OER is almost 1 showing that the HCP and ACP are almost identical.

5.2.10 Step 10

5.2.10.1 Future Comfort Performance (FCP)

As can be seen from §5.2.5.3, the air quality is inadequate. One option to improve this in the future is to install a mechanical ventilation system. Two air inlets and one air extract were proposed to be installed as shown in Figure 5.7. The parameters of the air grilles are detailed in Table 5.1.

Table 5.1 – Parameters of Air Grilles

Parameter	Inlet (x2)	Extract
Dimensions	1200 x 200	2400 x 200
Speed	0.3 m/s	0.5 m/s
Temperature	23 °C	n/a
Humidity	40%	n/a
CO_2	450ppm	n/a

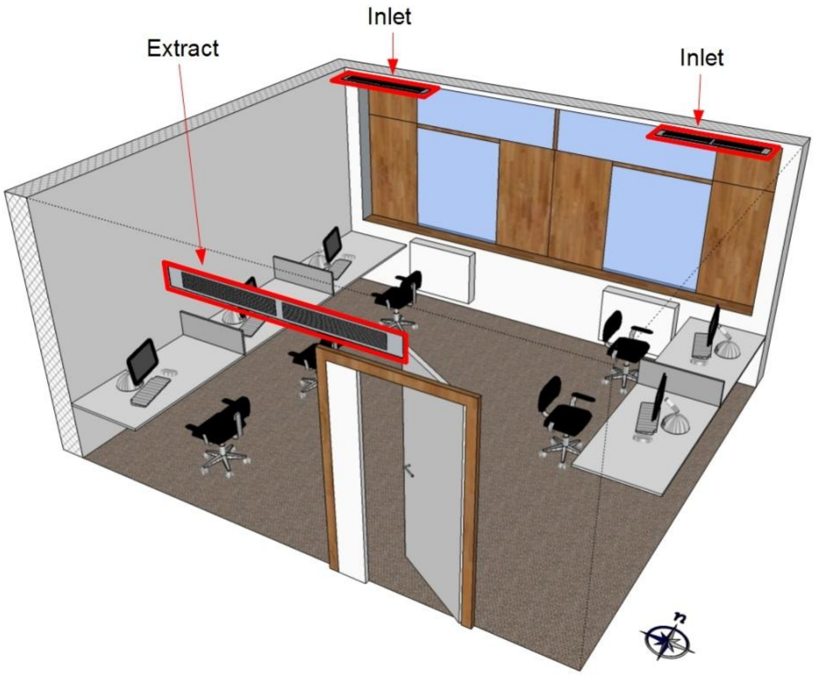

Figure 5.7 – Location of Air Inlet and Extract Grilles

The simulation was run using this data and a FCP of (5.5%, 1,242ppm) was calculated.

5.2.10.1.1 Analysis

The proposed installation of a mechanical ventilation system that produced this model resulted in an increase in the PPD of 0.5% from the optimum, which approximately equates to an increase in productivity of 0.25%. If that improved comfort was maintained for a full year that would equate to a gain of €500 to the employer for the room's five occupants. This value can be increased further by taking into account the improvement in air quality of 242ppm.

5.2.10.2 Comfort Rating – Future (CR-F)

The CR-F was calculated as (0.91PPD, 0.60CO_2) or (A [PPD], B [CO_2]). This compares the future to the ideal. This rating shows the proposed changes to the room would raise the optimum air quality from band C to band B and would maintain the thermal conditions in band A.

5.2.10.3 Benefit Analysis Rating (BAR)

The BAR was calculated as (1.09PPD, 1.20CO_2). This compares the future to the optimum. This rating shows that the proposed changes will improve the optimum comfort of the room.

5.2.11 Summary

5.2.11.1 Comfort Performances

Table 5.2 shows a chart of the Comfort Performances created during this test-case project. Figure 5.8 shows a chart of the Comfort Performances created during this test-case project.

Table 5.2 – Summary of Comfort Performances

Comfort Performance	Value
ICP	(5.0%, 750ppm)
RCP	(13.4%, 1,200ppm)
DCP	(7.9%, 5,423ppm)
CnCP	(10.1%, 3,392ppm)
ACP	(7.9%, 1,585ppm)
CaCP	(7.7%, 1,628ppm)
OCP	(6.0%, 1,484ppm)
CrCP	(6.8%, 1,515ppm)
HCP	(7.7%, 1,628ppm)
FCP	(5.5%, 1,242ppm)

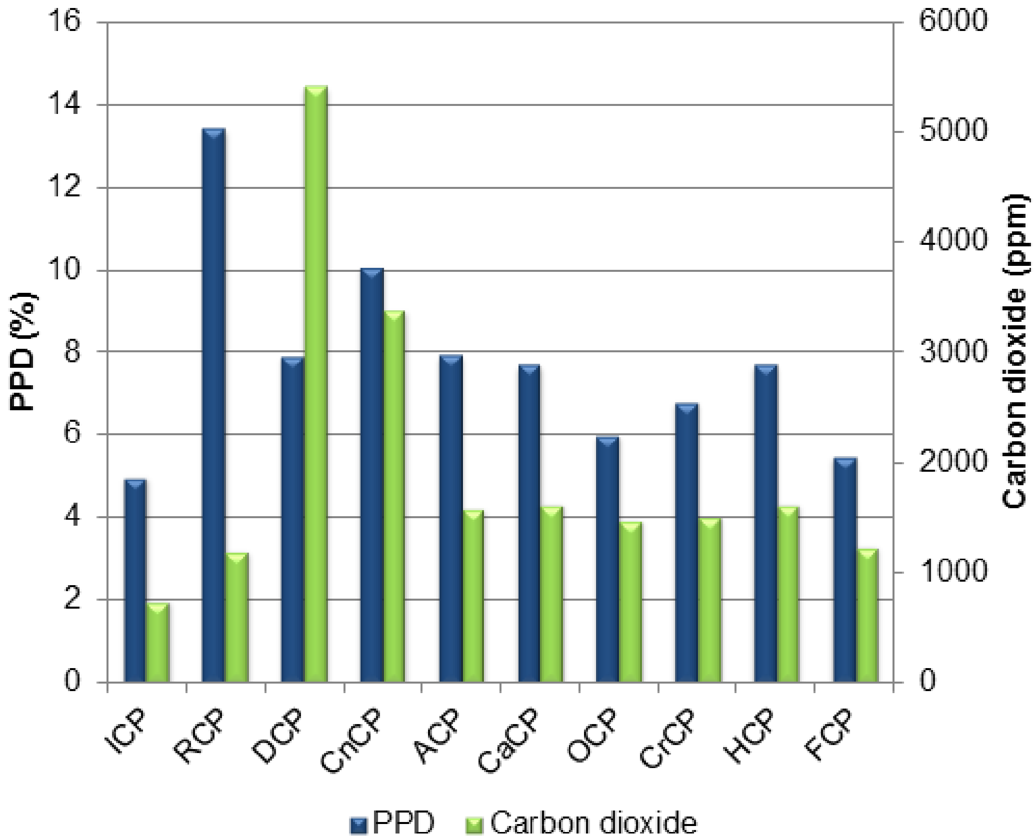

Figure 5.8 – Comfort Performances

5.2.11.2 Comfort Ratings

A summary of the Comfort Ratings created during this test-case project is given in Table 5.3.

Comfort Rating	Numerical Value	Banded Value
CR-R	(0.37PPD, 0.63CO_2)	(D, B)
CR-D	(0.63PPD, 0.14CO_2)	(B, E)
CR-C	(0.50PPD, 0.22CO_2)	(C, D)
PSR-P	(0.79PPD, 1.60CO_2)	N/A
CR-A	(0.63PPD, 0.47CO_2)	(B, C)
BSR	(1.70PPD, 0.76CO_2)	N/A
CR-O	(0.83PPD, 0.51CO_2)	(A, C)
OSR	(0.76PPD, 0.94CO_2)	(B, A)
PSR-A	(1.32PPD, 3.65CO_2)	N/A
CrSR	(0.86PPD, 0.96CO_2)	N/A
OER	(0.98PPD, 1.03CO_2)	N/A
CR-F	(0.91PPD, 0.60CO_2)	(A, B)
BAR	(1.09PPD, 1.20CO_2)	N/A

Table 5.3 – Summary of Comfort Ratings

Figure 5.9 shows a chart of the Banded Comfort Ratings, and Figure 5.10 shows the Non-Banded Comfort Ratings that were created during this test-case project.

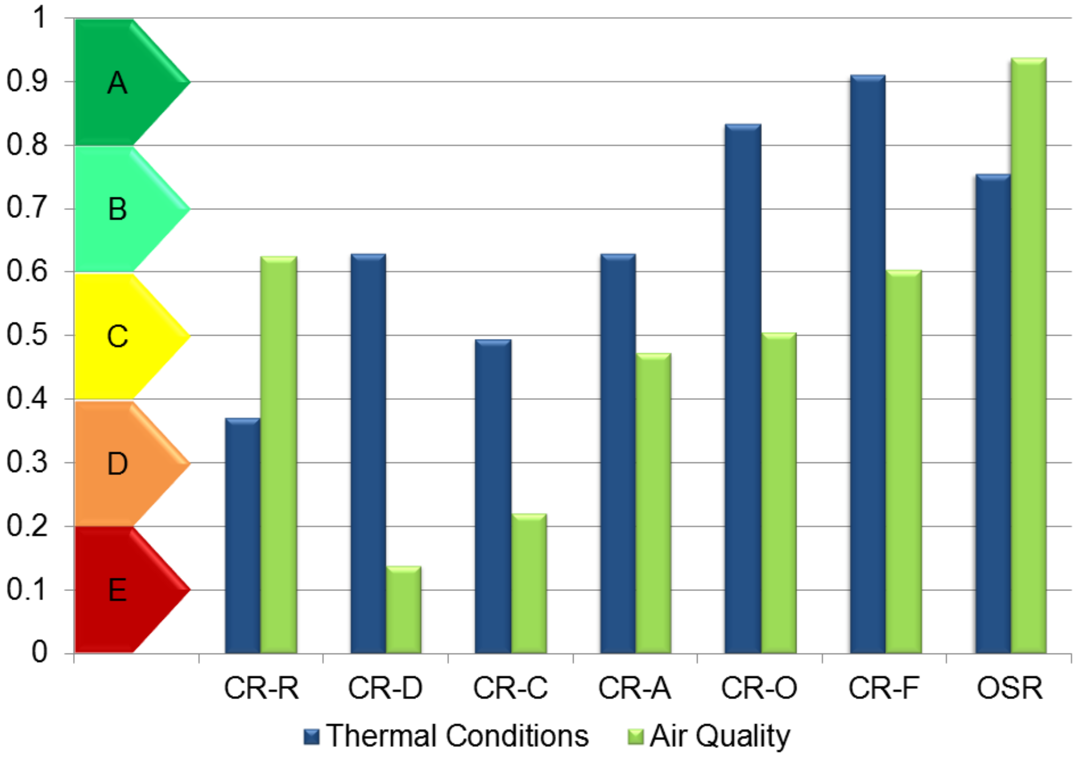

Figure 5.9 – Banded Comfort Ratings

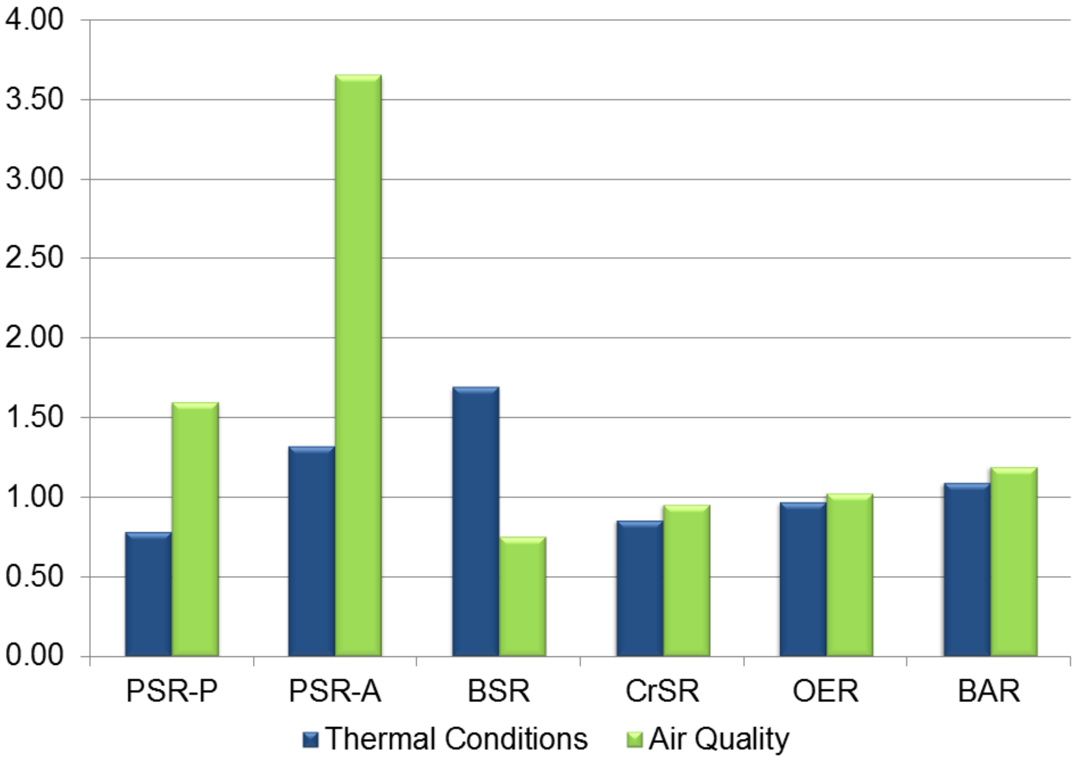

Figure 5.10 – Non-Banded Comfort Ratings

5.3 Comfort History

The Comfort History is a continuous descriptive record of the comfort throughout the project, with a focus on documenting the items and activities, proposed and implemented, which could potentially affect comfort. Therefore, for this test-case project the Comfort History is the information contained in §5.2. This section contains a continuous record of the comfort throughout the test-case project. As each sub-section was written it was stored in the BIM and linked to the relevant comfort entity. For example, the information on the Ideal Comfort Performance in §5.2.1.1 was recorded in a text file, stored in the BIM and linked to the Ideal Comfort Performance in the BIM.

5.4 Knowledge Use Scenarios

The following sections, §5.4.1 to §5.4.3, use the information from the test-case to develop the description of the Knowledge Use Scenarios specified in §3.4.

5.4.1 Scenario 1 – Designer

Figure 5.11 graphs the ICP, RCP, DCP, CnCP, and OCP for this test-case. These Comfort Performances are the most useful models for the Designer. From these it can be easily seen that the design air quality is not within the required air quality. Therefore, future designs would benefit from incorporating changes that would address this issue. These performances show that the changes made during construction improved the air quality and it would be beneficial to review these changes to see if they could be incorporated into future designs. Both the DCP and CnCP were poor at predicting the OCP. It would be beneficial to investigate the reasons for these differences and implement appropriate changes when calculating future DCPs and CnCPs.

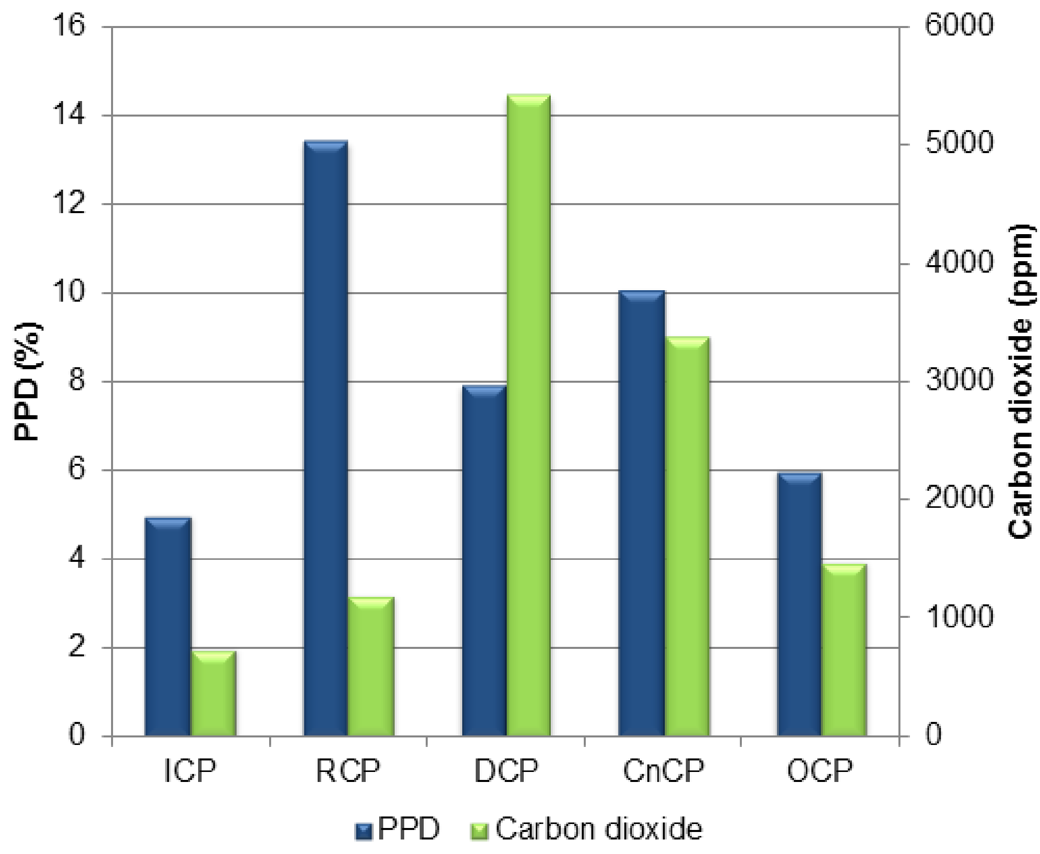

Figure 5.11 – Comfort Performances Useful to the Designer

5.4.2 Scenario 2 – Project Manager

Figure 5.12 shows the CR-R, CR-D, CR-C, and CR-O and Figure 5.13 shows the PSR-P and PSR-A. These provide useful insights for a Project Manager. The CR-D, CR-C and CR-O show the progression of comfort through the project stages. The CR-C shows that the changes made during construction reduced the thermal conditions from band B to C but improved the air quality from band E to D. These changes could be investigated in order to identify areas for improved air quality in future designs. Both the CR-D and CR-C did not accurately predict the CR-O. This shows that the simulations used in design and construction could be improved to predict actual conditions more accurately, and improve designs. The Project Manager’s goal is to have the CR-D, CR-C and the CR-O as similar as possible. The PSR-P shows that the construction process did not implement the design accurately. The changes that were made during construction improved the air quality but reduced the thermal conditions. The PSR-A shows that the project did not achieve what was set out in the design.

However, the changes, intentional or not, that caused this actually improved on the design comfort.

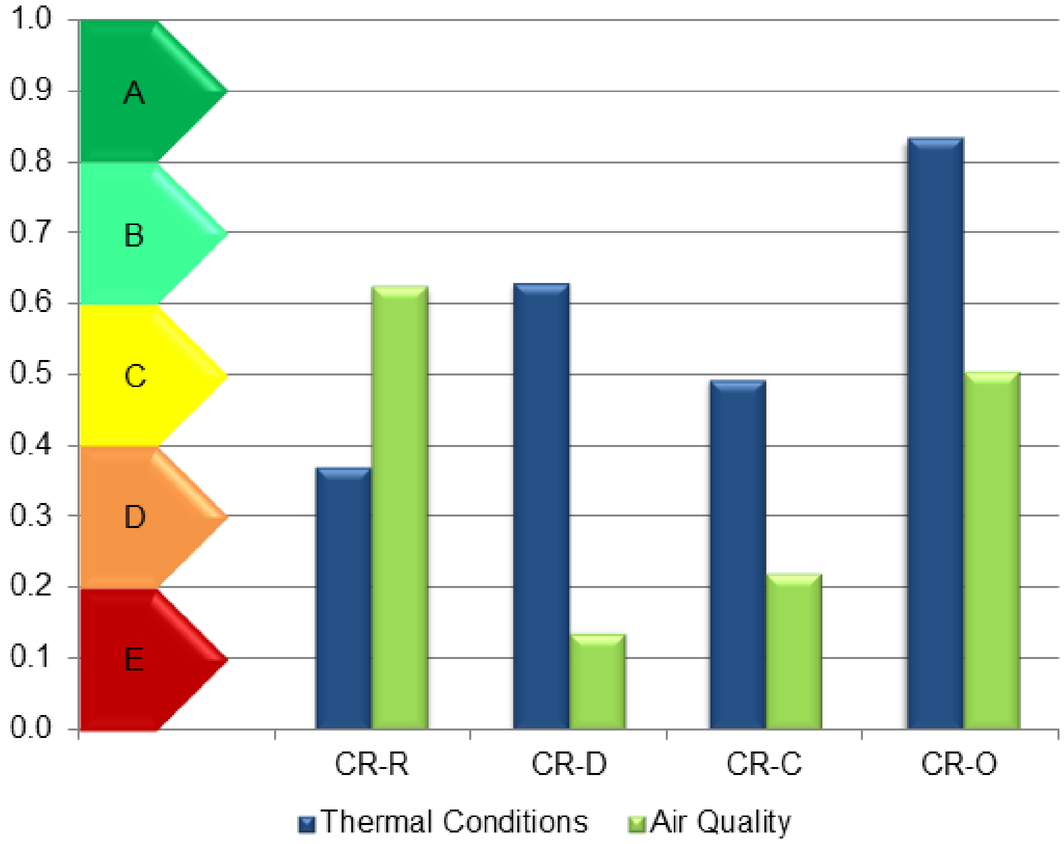

Figure 5.12 – Banded Comfort Ratings that are Useful to the Project Manager

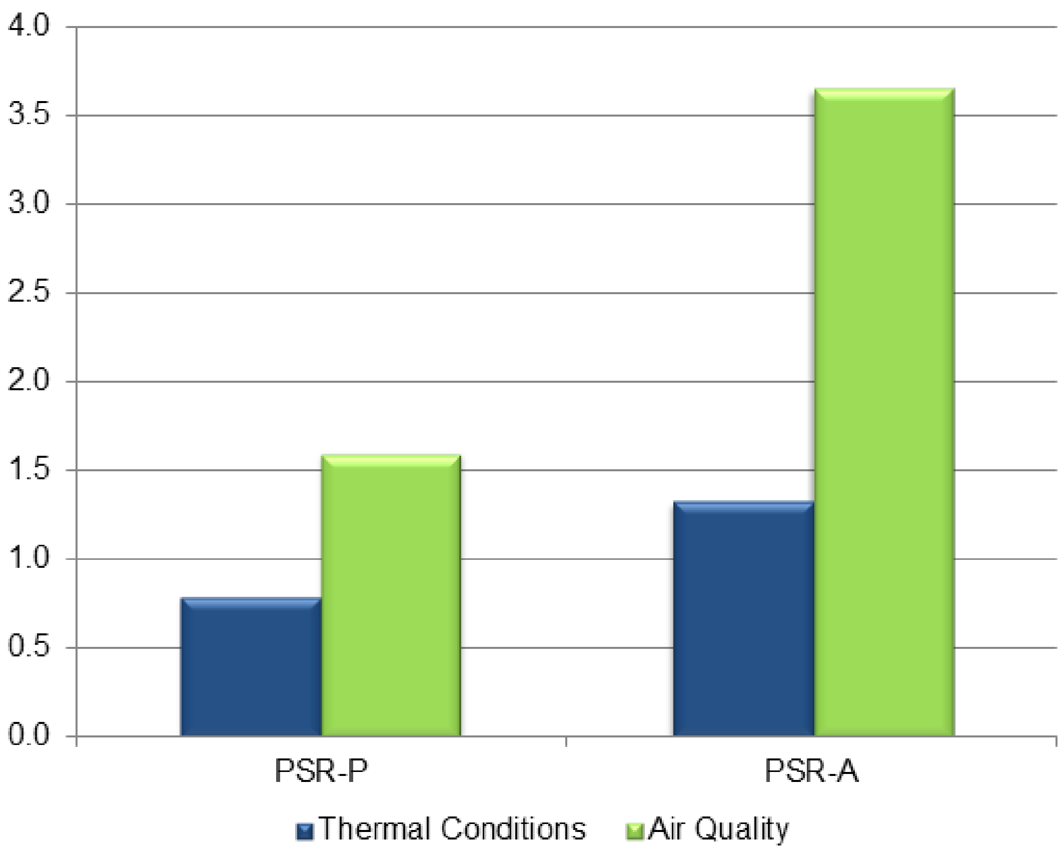

Figure 5.13 – Non-Banded Comfort Ratings that are Useful to the Project Manager

5.4.3 Scenario 3 – Operation

5.4.3.1 Owner

Figure 5.14 shows the OSR, and CR-F and Figure 5.15 shows the BSR and BAR. These provide useful insights to the Owner. The BSR shows that the required standards are not being met as the air quality value is below 1. This informs the owner that either the operation of the room or the systems servicing it need to be changed to meet regulations. The OSR shows that the actual comfort of the room is below the optimum comfort achievable in the room, which indicates to the owner that the operation could be improved. The OSR allows the owner to compare the operation of different buildings irrespective of type. The CR-F shows the comfort level achievable in the room if a mechanical ventilation system was installed in the room, as specified in §5.2.10.2, and the BAR shows that these alterations also improve on the existing optimum.

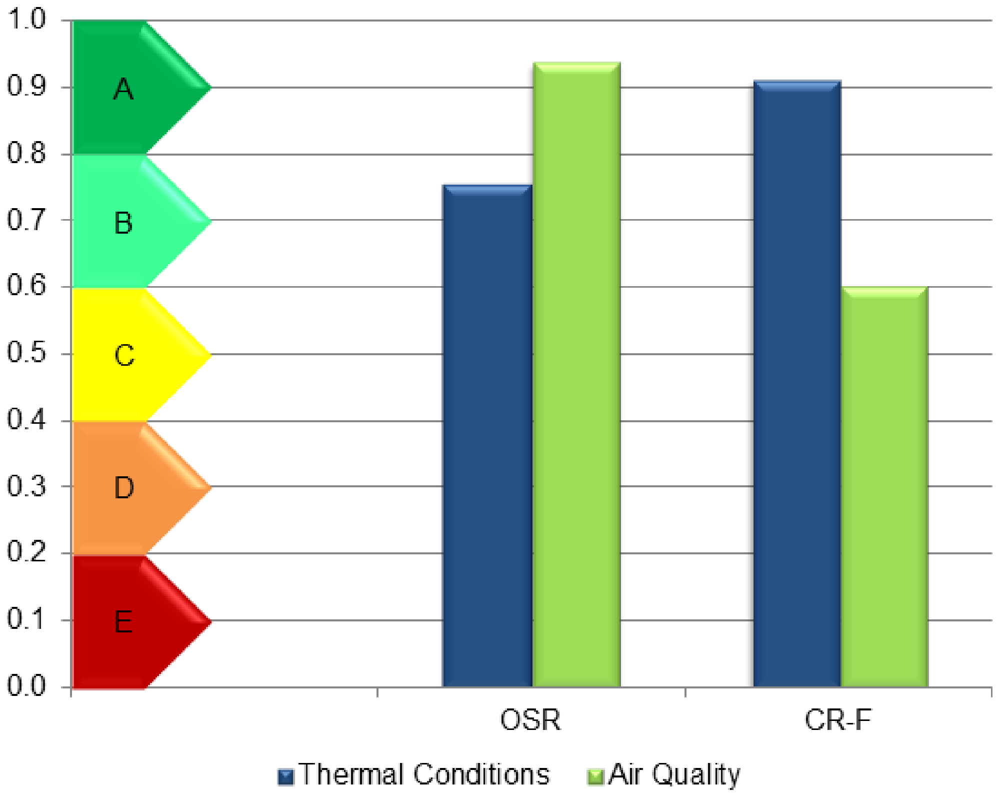

Figure 5.14 – Banded Comfort Ratings that are Useful to the Owner

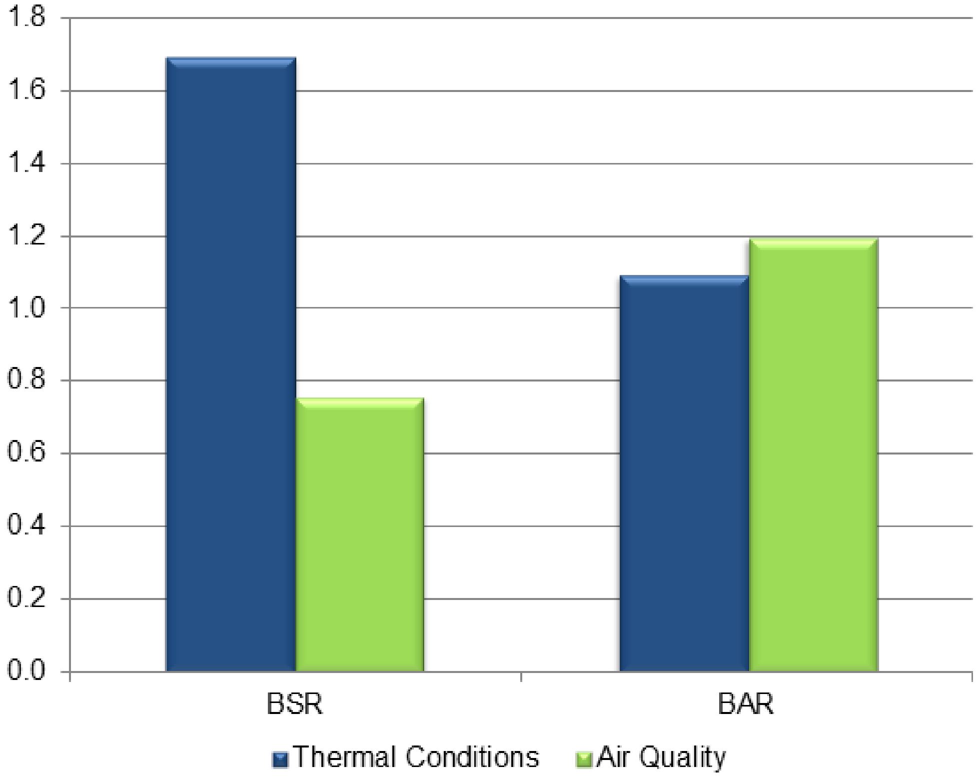

Figure 5.15 – Non- Banded Comfort Ratings that are Useful to the Owner

5.4.3.2 Operator

Figure 5.16 shows the CR-R, CR-A, CR-O and OSR. Figure 5.17 shows the BSR, PSR-P and OER and Figure 5.18 shows the ICP, RCP, ACP, OCP, CrCP and the HCP. These provide useful insights to the Operator. The OSR shows that the building is operating close to its best with regards to air quality but the thermal conditions aspect could be improved from band B to band A. The ACP and OCP can be compared to give a similar insight. The BSR shows that the environment is not being operated within the legal requirements because the air quality aspect of the BSR is less than one. The CR-A and CR-R can be compared to give a similar insight. The CrSR shows that the model based control is working reasonably well. The Operator could use this as an alarm to warn them if the CrCP is outside acceptable thresholds. The OER shows that there are no faults in the operation of the room. The Operator could use this as an alarm to warn them if the environmental operation of the room is not operating as predicted and, in turn, if there is a fault in the HVAC system. The ACP, OCP, CrCP, and HCP show the level of comfort at the different stages of operation. Using this information along with the Comfort History allows the Operator to make informed decisions about the building operation.

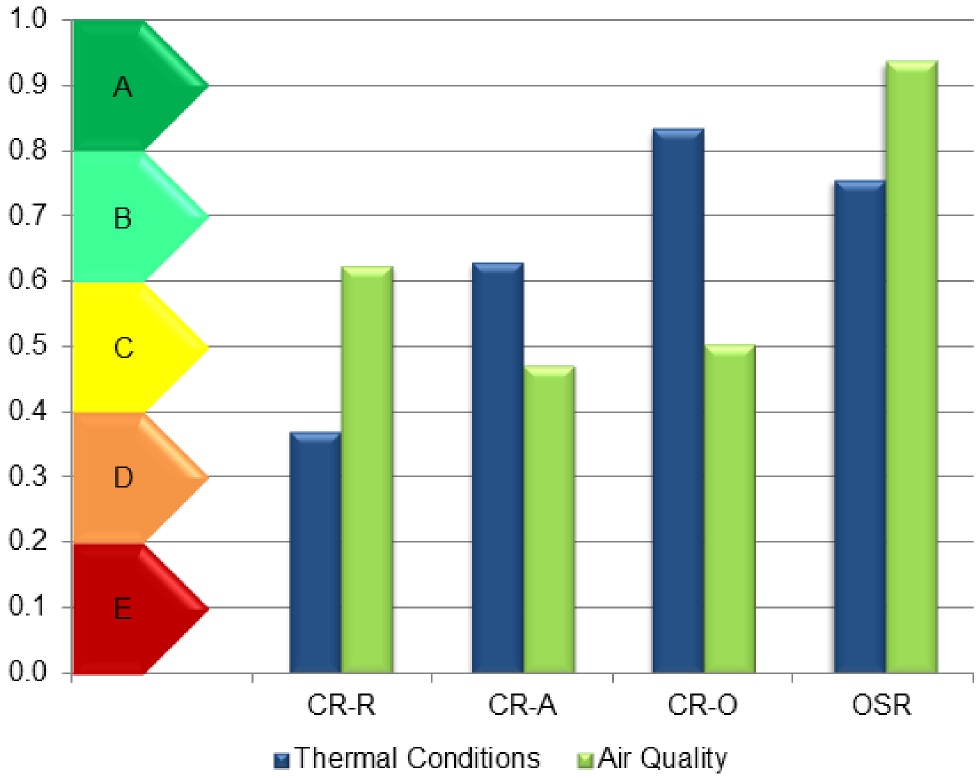

Figure 5.16 – Banded Comfort Ratings that are Useful to the Operator

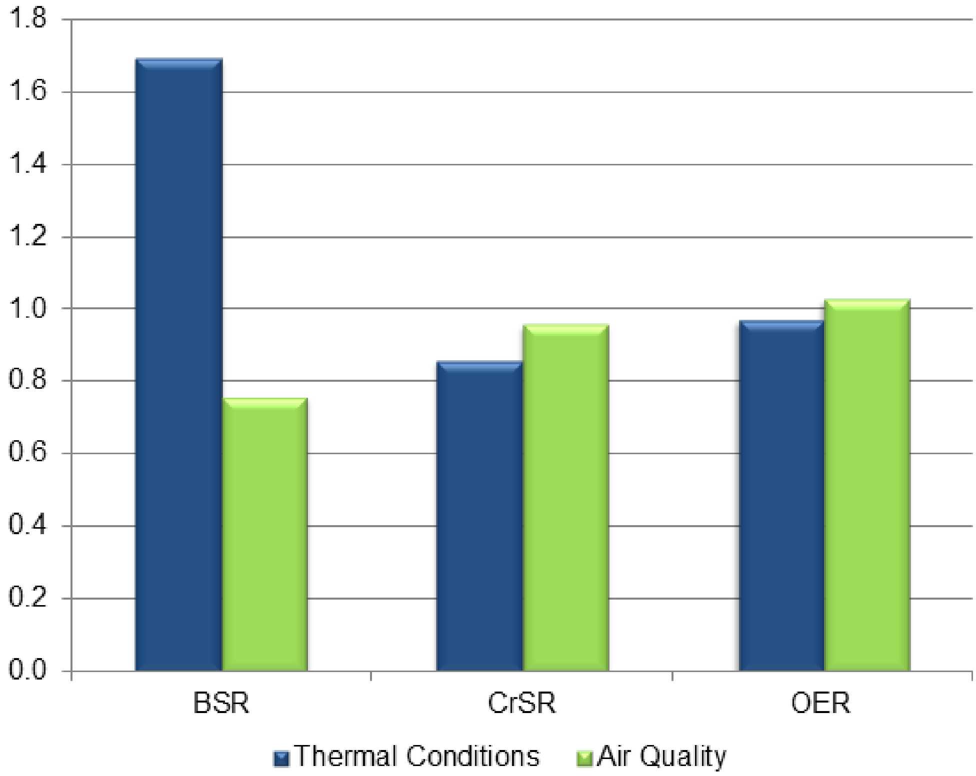

Figure 5.17 – Non-Banded Comfort Ratings that are Useful to the Operator

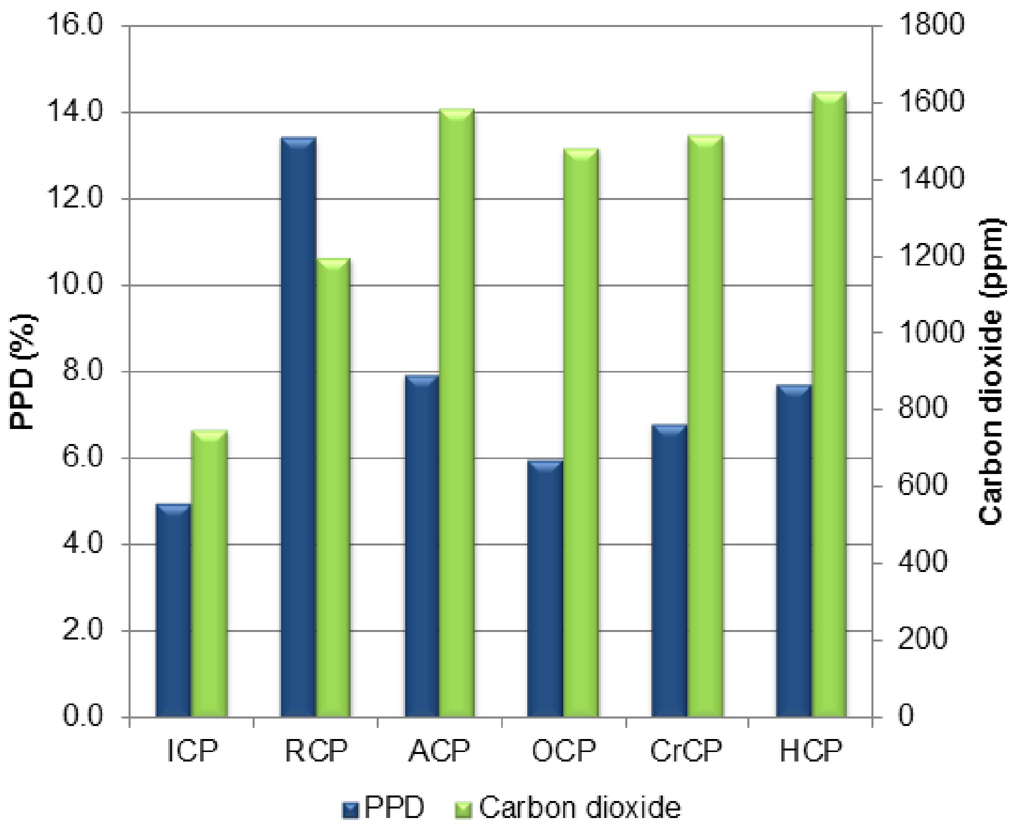

Figure 5.18 – Comfort Performances that are Useful to the Operator

5.5 Analysis of the Test-Case

The test-case showed that the LCMS system was able to create, store, and make available the Comfort Performances, Comfort Ratings, and the Comfort History as specified by the ComMet methodology. This shows that LCMS can operate effectively and satisfy the requirements of ComMet. The test-case showed that re-use of the comfort knowledge was possible, such as, re-using the Comfort Performances generated early in the test-case project to generate Comfort Ratings. These Comfort Ratings were used to identify options for improved comfort in the room. For instance, the OSR identified that the operation was not at its optimum. This shows that the ComMet methodology enables comfort knowledge gained at each stage of a building project to be captured, stored and made available to future project stages and future projects in a consistent and unambiguous manner, and that this can improve the occupant comfort in the indoor environment.

Chapter 6

Conclusion

6.1 What's New?

§6.1.1 to § 6.1.4 identify the novel developments created by this research.

6.1.1 BabySteps

BabySteps is an approach for implementation. It states that for an innovation to be adopted into the industry it must be implementable through a number of small changes. However, although the BabySteps approach guided aspects of this research, it still remains an untested theory since this research has not been implemented into the industry.

6.1.2 ComMet

The ComMet methodology enables the re-use of comfort knowledge in order to help improve comfort. To do this it captures, stores, and makes available comfort knowledge throughout the BLC through the use of Comfort Performances, Comfort Ratings, and a Comfort History.

Comfort Performances quantify the comfort of the indoor environment at each stage of the BLC. Comfort Ratings are generated from comparing different Comfort Performances. They provide extra information on the comfort of the indoor environment, which is not easily determinable from the individual performances. A Comfort History is a continuous descriptive record of the comfort throughout the project, with a focus on documenting the items and activities, proposed and implemented, which could potentially affect comfort. Each aspect of the Comfort History is linked to the relevant comfort entity.

6.1.3 LCMS

The LCMS system is an implementation of the ComMet methodology. To achieve this LCMS combines:

- Building Standards;

- Simulation Software;
- The Egg-Whisk Network;
- Spreadsheet Software;
- Text Editing Software;
- And a Central Knowledge Storage and Web-Based Access technologies.

Traditionally, controlled laboratory experiments provided the information needed to improve comfort and now the LCMS system can be used to turn the real world into a laboratory to provide better information to improve comfort, and health, further;

6.1.4 Egg-Whisk Network

The Egg-Whisk Network is a specially designed mobile network of wireless sensing motes, which can be used to record the detailed comfort conditions of an operational indoor environment.

6.2 Proof of Concept

"Every day is a school day". The following is a summary of the preceding research and outlines the main steps taken in order to prove the hypothesis.

Chapter 2 is an in-depth review of comfort, the construction industry and previous proposed information systems. This review identified the following three main points:

1. Improving comfort has social, health and economic benefits;
2. There is a lack of knowledge re-use in the construction industry, which can result in poor comfort of indoor environments;
3. Previous proposals to improve information re-use did not get successfully adopted into the industry.

Chapter 3 shows that improving the management of comfort knowledge can improve comfort.

Chapter 4 describes the ComMet methodology that enables comfort knowledge to be captured, stored and accessed throughout the building life-cycle, which allows it to be re-used in future stages of the project and in future projects. It does this by creating Comfort Performances, Comfort

Ratings and a Comfort History, which create a comprehensive record of the comfort throughout the BLC. These are stored and made available in a common format in a central location, which allows them to be re-used ad infinitum.

Chapter 5 describes the LCMS system, which is an implementation of ComMet. It describes how ComMet could be implemented in the industry while also satisfying the BabySteps approach. It uses current and emerging technologies, most notably the Egg-Whisk Network, to achieve a successful implementation of ComMet.

Chapter 6 describes the successful trail of LCMS and how the comfort of the test-case space was improved through its use.

To summarise:

- An improvement in the management of comfort knowledge is enabled by the ComMet methodology;
- ComMet is implemented by the LCMS system;
- LCMS identified ways to improve the comfort of the test-case room.

Therefore, improving the management of comfort knowledge can improve comfort. QED :-)

6.3 Future Work

To paraphrase Winston Churchill, even with constant progress the road of improvement is ever-lengthening. There is always room for improvement. The ComMet methodology and the LCMS system are no exception to this rule and the following two sections describe some planned improvements to both.

6.3.1 ComMet in the Future

ComMet will be expanded to include more parameters in order to give a more comprehensive definition of comfort. The two main parameters to be considered are Visual Conditions and Acoustic Conditions. Visual Conditions are significant because lighting affects occupant comfort by making tasks easier to perform and contributing to an interior that is considered satisfactory and even inspiring by providing emphasis, colour and variety

[14]. Acoustic Conditions are important because noise affects occupant comfort by causing annoyance, interference to speech intelligibility, or hearing damage [14].

6.3.2 LCMS in the Future

It is proposed to improve the LCMS system. The Egg-Whisk mote will be upgraded to include an on-board radiant sensor. This will allow the mote to give a complete thermal comfort measurement. The range of the CO_2 sensor will be increased. §5.2.5.1 shows that the CO_2 sensor's maximum limit of 2,000ppm was not adequate for measuring CO_2 concentrations in an office space. This is despite this limit being sixty six per cent greater than the maximum acceptable limit for the CO_2 concentration in an office. The mote will also be upgraded to include additional sensors to detect other air pollution substances that affect comfort.

One upgrade option for the BIM is to use the data warehouse being developed by ITOBO [107] as it works on similar technology as the LCMS system. As the system evolves, the Web-Based Access will be required to display and manage large volumes of information in clear, understandable formats. The success of LCMS relies on the usability of this web-access and its associated web-services. As previously stated the IFC schema is not currently able to optimally support all of the components of LCMS. A system or a development to the IFC schema is required in order to enable the information in CSV files, CFD files and text files to be easily incorporated into an IFC BIM. For example, it would be very beneficial if a spreadsheet tool could communicate directly with an IFC BIM.

6.4 Other Future Possibilities

Apart from helping to improve comfort by improving comfort knowledge management, this research has other possible future applications. Personal Preference Models are one such application. Questionnaires have been used for many years to determine the occupant's response to comfort conditions. By using interactive questionnaire applications on occupant's PCs these questionnaires are currently being developed to create personalised equations, which model the occupant's response to the comfort conditions. A key part to developing these Personal Preference Models is the accurate measurement of the comfort conditions experienced by the occupant. This information can be provided by ComMet.

The goal of Energy Efficiency is to reduce the energy needed to provide the required comfort conditions. ComMet compliments this goal as it gives a comprehensive measure of the comfort at all stages of the BLC and so enables the success of energy efficiency to be quantified more accurately at each stage.

Localised HVAC Supply is the future of HVAC. This is the supply of HVAC directly to where it is required [11], i.e. supplying heating and ventilation as close to the occupant as possible. This Localised HVAC Supply requires localised measurement, which can be provided by LCMS.

LCMS can provide Real-time Information for Real-time Control. Real-time Control can be either manual or automatic and LCMS can be used for both.

Comfort is a complex entity with many interacting variables and all people cannot be expected to understand it. Therefore providing real-time comfort information to occupants allows them to make informed decisions about manual HVAC. The LCMS system can provide this information. If an occupant feels uncomfortable due to a high CO_2 concentration, it is likely that the occupant does not know that a high CO_2 is the reason for the discomfort and would be unable to rectify the situation. LCMS can identify the cause of the discomfort and inform the occupant that the window should be opened in order to reduce the CO_2 concentration and possibly that the heating should be increased to compensate for the low temperature air that will flow through the window.

Real-time information is required for automatic control for two purposes. Firstly, it is required to inform the control system of the conditions in the space. LCMS can provide this information to a high detail. Secondly, real-time information is required to inform the occupants as to why the HVAC system is operating in a particular way. Lack of information is a major cause of automatic controls being disabled in HVAC systems. LCMS can provide occupants with information on the comfort conditions in a space and enable them to understand why automatic controls, such as windows, are operating.

6.5 Maintain Focus

Albert Einstein (physicist) stated that *"Concern for man and his fate must always form the chief interest of all technical endeavours. Never forget this in the midst of your diagrams and equations"*. It is always important to remember the goal of this research. The ultimate purpose of the new approach, principle, methodology, system, and technology, developed by this research is to improve the comfort, health and survival of people.

People are the priority.

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Annex A

Thesis Summary

A.1 Current Situation

Evolution has conditioned human beings to optimise what is under their control in order to promote their survival [1], [2]. This instinct currently manifests itself as a drive to develop international climatic agreements [3] and to promote, better living environments [4], energy efficiency [5], and building sustainability [6], [7]. Currently however, optimisation of indoor environments is largely focused on energy efficiency rather than the promotion of optimal comfort for occupants.

Occupants should be the dominant consideration in designing, constructing, and operating buildings both in terms of function and cost. It was determined in 1989 that for the average business in the USA, salaries exceed the combined office costs of energy, maintenance, annualised construction and rental by a factor of 100. Therefore, a 1% increase in employee productivity would justify a doubling of the other costs [8]. H.F. Levy, P.E. Professional Engineer & Life Member of ASHRAE, put it best when he said *"our real customer is the occupant, not the building."* Simply put, optimising comfort optimises productivity, which optimises costs.

A.1.1 Comfort

Comfort can be defined as *that condition of mind that expresses satisfaction with the environment* [9]. The environmental factors considered to affect occupants' satisfaction with the environment are thermal comfort, visual conditions, acoustic conditions, air quality, vibration, electromagnetic fields and electrostatic conditions [10]. In the absence of definitive scientific grading of the relative importance of these factors, there is a strong perception that thermal comfort and air quality are the most significant. These factors are the focus of this research and the term 'comfort' can be taken as a combination of thermal comfort and air quality. For this research the thermal comfort is given by the predicted percentage dissatisfied (PPD) value [10]. The data used to calculate the PPD are the following environmental factors:

- Air speed;
- Air temperature;
- Air humidity; and
- Radiant temperature.

Along with the following personal factors:

- Clothing level; and
- Activity level.

For this research the air quality is given by the CO_2 level, which is a good indicator of air quality in areas where bio-effluents from occupants are the most significant pollution in the environment [9].

A.1.2 The Economics of the Indoor Environment

Improving the comfort of the indoor environment has proven health and productivity benefits, and, therefore, financial benefits. The indoor environment is regarded as more important to productivity than job dissatisfaction and job stress [11], and has a major effect on absenteeism [12].

A significant aspect of the indoor environment is thermal comfort. Occupant thermal discomfort in the indoor working environment directly affects job performance which has a significant financial affect [13], [14]. A 10% reduction in comfort can result in a 5% reduction in productivity, which can result in a loss of over €2,000 per average employee in Ireland. Refer to §1.4.2 for more details.

Air quality is a significant factor affecting the indoor environment. Indoor air quality (IAQ) is directly proportional to occupant health [13]. Indoor air pollution is responsible for 1.6 million deaths worldwide each year. That is one every twenty seconds [15]. Along with improved health, the productivity benefits resulting from improving indoor air quality can be up to 60 times higher than the associated increased costs [16].

A.1.3 Construction Industry

Currently, the majority of indoor environments are designed, constructed and operated by the construction industry. Therefore, in order to achieve the social and financial benefits of improved environmental comfort the construction industry needs to be improved. The construction industry is quite unique as it is a fragmented industry [17], [18] containing many different elements, such as disciplines, companies, systems, software, etc. These elements come together for temporary, short term, once-off projects [19]. Improving a temporary, non-repetitive process, as one unit is an immense task. However, the elements are re-used repeatedly throughout the industry [20]. Therefore, by improving each element individually, the process as a whole can be improved incrementally. This research identified that improving the re-use of information, specifically in relation to comfort, is one such incremental improvement.

The re-use of information is poor mainly due to poor integration of the three stages of the building life-cycle: design, construction and operation. To improve design, operation information needs to be made available in a usable format so it can then be used to calibrate design simulation models, and subsequently improve future designs [21]. However, the transfer method used for building information is inadequate and often causes unnecessary expense and errors [22]. These errors are usually caused by difficulty locating data, transformation of data between differing formats, and transferring large quantities of data [23]. Current access to operation data on indoor environments, which can be used to assess and improve comfort, is also inadequate [24]-[26]. In fact, a system to record actual comfort in operational buildings is almost non-existent [27].

A.1.4 Previous Proposed Systems

Though not specifically designed for comfort, there are numerous research groups promoting on-line data-centric collaboration to improve the use of information in the construction industry [28]. Building information modelling (BIM), which is the process of providing a single, logical, consistent source for all information associated with a building, is the most popular proposed system to enable improved information use. To-date, electronic document management (EDM) is the only industry-wide method currently improving collaboration [29]. Electronic document management does not have the collaboration potential of BIM, because it does not store information in a consistent manner and instead stores information in various document formats. So, if BIM is an improvement on EDM, why then has it not been fully adopted by industry?

A.1.5 Implementation of Innovations

Many proposed BIM systems have come from some of the most accomplished research groups in the field. The systems are comprehensive and advanced, integrating various differing construction components into one complete system. The fact that the industry is generally unchanged from its document based roots demonstrates that these systems have been unsuccessfully adopted and applied in the industry.

It is common knowledge that the construction industry is reluctant to change [23], [30]. It is *not* common knowledge *why* the construction industry is reluctant to change. Or more accurately, it is not *commonly asked,* why the construction industry is reluctant to change.

Everett M. Rogers identified five criteria for diffusion of innovation, shown in Table A.1, that must all be met for an innovation to be successfully adopted into an industry [31]. One key point to note is that the majority of construction sector companies are small to medium enterprises (SME). In fact, 96% of the EU's 2.3 million construction sector enterprises employ less than 20 people [32]. So in this context, if the previous proposed systems are analysed under the five criteria for diffusion of innovation as shown in Table A.1, the reason for non-adoption becomes clear. It seems most of the previous proposals required too large a change for them to be successfully adopted by the industry.

This research proposes a different approach. As Mark Twain (author) once wrote *“Habit is habit and not to be flung out of the window by any man, but coaxed downstairs a step at a time.”* That is, large changes to established systems are easiest to achieve through a number of small changes or

‘BabySteps’. Analysis of this approach under Rogers’ criteria is also shown in Table A.1.

Table A.1 – Diffusion of Innovation Criteria

Diffusion of Innovation Criteria	Previous Proposed Systems	BabySteps
Relative Advantage	The proposed systems are too large and, therefore, too expensive to provide any benefit to SMEs.	Small changes are cheaper to implement and are also more acceptable to employees, which improves productivity.
Complexity	BIM is complex but large changes compound this problem and so the complexity of the systems exceeded the ability of SME's to adopt them.	Small changes are less complex.
Compatibility	The proposed systems have not been compatible with the current system for managing information being used in the industry. Some actually require the entire current system to be changed.	Small changes are usually more compatible with, and are easier to incorporate into, the current system.
Trial-ability	Industry cannot try the new proposals because they are too large and expensive.	Small changes are easier to trial because of lower cost and employees are more willing to try them.
This table continues on the next page.		

Diffusion of Innovation Criteria	Previous Proposed Systems	BabySteps
This table starts on the previous page.		
Observe-ability	Some BIM demonstrations have been successfully completed. However, these were not enough to overcome the lack of compliance with the other four of Rogers' criteria.	Small changes are easy to demonstrate.

Refer to §1.7 for a detailed explanation of the points in Table A.1.

A.2 Room for Improvement

A.2.1 Problem Definition

Indoor environments work. The current system for providing them also works. However, there is always room for improvement. The main inefficiency identified during this research is that there is a lack of knowledge management throughout the building life-cycle and this adversely affects occupant comfort. Firstly, this is because existing knowledge is managed in a way that makes it unavailable for future use. Secondly, the comfort history or the continuous record of comfort through the building life-cycle is not available. And lastly, most of the previous attempts to improve the information management were not successfully adopted. It is deduced that this is because they did not comply with a suitable implementation approach such as BabySteps.

A.2.2 Hypothesis

The principle to be learned from the problem definition is that improving the management of comfort knowledge can improve comfort.

The following hypothesis was derived from this principle:

The occupant comfort in the indoor environment can be improved if the comfort knowledge gained at each stage of a building project is captured, stored and made available to future project stages and future projects in a consistent and unambiguous manner.

A.2.3 Improvements

The improvement proposed by this research is to improve the management of comfort knowledge and this can enhance the occupant comfort in the indoor environment. This will be achieved by creating a methodology that will enable knowledge, as it is created, to be captured, stored and made available. This means that this knowledge can be re-used in future stages of the project and in future projects. This can integrate the project stages further, which can:

- Improve designs by allowing design success to be measured;
- Reduce expense and errors by improving the information transfer method;
- Improve operation by allowing the building operator to access design information.

A.3 The ComMet Methodology

A.3.1 Overview

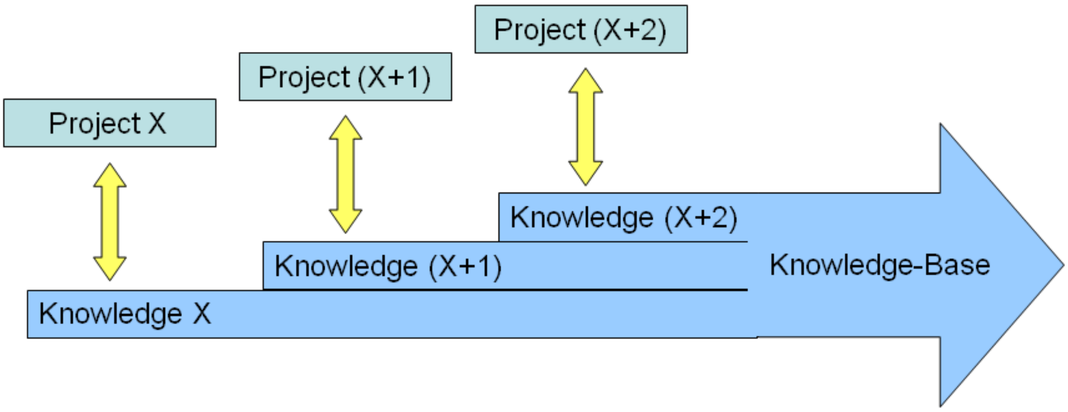

Figure A.1 – Knowledge Re-Use

To improve knowledge re-use, a new methodology to manage knowledge through the building life-cycle was developed. The comfort methodology, named ComMet, enables knowledge gained at each stage of a project to be available to future project stages and future projects as shown in Figure A.1. ComMet specifies that all knowledge must be captured, stored and made available in a consistent and unambiguous manner.

A.3.2 Knowledge

A.3.2.1 What is Knowledge?

Knowledge is the acquaintance with facts, truths, or principles, as from study or investigation. Knowledge is information with context and so access to information is crucial to improving knowledge. Knowledge is what is important and it needs to be re-used more [17], [33], [34], [18], [20], [32], [35]-[38]. Improving the re-use of comfort knowledge can enable occupant comfort to be improved. In fact occupant health can be directly improved by simply increasing the occupant's knowledge of their environment, as it improves their ability to understand and control it [39].

A.3.2.2 Comfort Knowledge Sources

ComMet defines and captures comfort knowledge through the creation of the following comfort knowledge sources:

- Comfort Performance– These are simplified numerical representations of the comfort of the indoor environment. Comfort Performances quantify the comfort at each stage of the building life-cycle using standard comfort metrics;
- Comfort Ratings - These are a means of classifying the comfort conditions of the indoor environment according to an appropriate standard. Comfort Ratings are generated by comparing different Comfort Performances. Comfort Ratings provide additional information relating to the comfort conditions of the indoor environment, which is not readily determined from the individual Comfort Performances.
- Comfort History – This is a continuous descriptive record of the comfort throughout the project, with a focus on documenting the items and activities, proposed and implemented, which could potentially

affect comfort. Each aspect of the Comfort History is linked to the relevant comfort entity it references.

A.3.2.3 Comfort Performances

Comfort Performances quantify the comfort conditions at each stage of the building life-cycle at a specified location. There are typically ten Comfort Performances and the sequence in which they are created during a project is shown in Figure A.2. For clarity, the performances are divided into project stages, and the data sources needed to generate the individual Comfort Performances is specified. These data sources are, building standards, computer based simulation models, and physical data measurement systems. A description of each and how they are created is given in Table A.2.

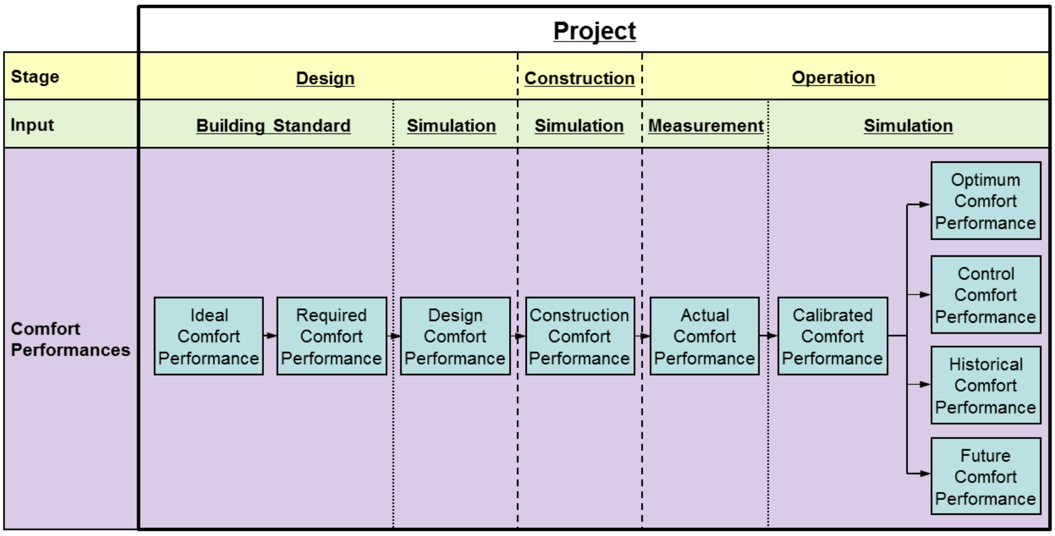

Figure A.2 – Comfort Performance Creation Sequence

Table A.2 – Comfort Model Descriptions

Comfort Model	Definition	Inputs Required	Creation Tool	Non-Model Outputs
Ideal Comfort Performance (ICP)	Ideal comfort levels that can be achieved	Building Standards	N/A	N/A
Required Comfort Performance (RCP)	Minimum required comfort levels to be achieved	Building Standards	N/A	N/A
Design Comfort Performance (DCP)	Expected comfort levels based on the design data	Comfort Model and Design Data	Simulation Tool + Calculation Tool	N/A
Construction Comfort Performance (CnCP)	Expected comfort levels based on the construction data	Comfort Model and Construction Data	Simulation Tool + Calculation Tool	N/A
Actual Comfort Performance (ACP)	Actual comfort levels achieved	Stage 1: Actual Environment	Measure-ment Tool	Actual Environ-mental Data

This table continues on the next page.

Comfort Model	Definition	Inputs Required	Creation Tool	Non-Model Outputs
This table starts on the previous page.				
		Stage 2: Actual Environ-mental Data and Building Data	Calculation Tool	N/A
Calibrated Comfort Performance (CaCP)	Simulated Comfort Performance calibrated to match the ACP	Comfort Model and the ACP	Simulation Tool + Calculation Tool	N/A
Optimum Comfort Performance (OCP)	The optimum comfort levels achievable with the actual environment and HVAC systems	Comfort Model and comfort strategies	Simulation Tool + Calculation Tool	Optimum Comfort Strategy
Control Comfort Performance (CrCP)	Expected comfort levels based on the predicted environmental data and adjusted control strategy	Comfort Model and predicted environment-al data	Simulation Tool + Calculation Tool	Control Strategy
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Comfort Model	Definition	Inputs Required	Creation Tool	Non-Model Outputs
This table starts on the previous page.				
Historical Comfort Performance (HCP)	Expected comfort levels based on the historical environmental data and employed control strategy	Comfort Model and historical environment-al data	Simulation Tool + Calculation Tool	N/A
Future Comfort Performance (FCP)	Expected comfort levels based on future design data for the current environment	Comfort Model and Future Design Data	Simulation Tool + Calculation Tool	N/A

A.3.2.4 Comfort Ratings

The Comfort Ratings are comparisons that generate new information from the information in the Comfort Performances. The information is clear, unambiguous, and requires little comfort knowledge to understand. The comparisons translate the complex definitions of comfort in the Comfort Performances into universally understandable ratings, which are usable by the expert and non-expert alike.

The ratings are in the form of:

$$\textit{Comfort Rating} = \frac{\textit{Comfort Performance (dividend)}}{\textit{Comfort Performance (divisor)}} \qquad \text{(A.1)}$$

Where:

- Comfort Rating is the unit-less ratio of the divisor Comfort Performance to the dividend Comfort Performance;

- Divisor Comfort Performance is the Comfort Performance that is to be compared;
- Dividend Comfort Performance is the base model that the divisor Comfort Performance is to be compared to.

Some benefits of using ratios for these ratings are:

- They are unit-less, which reduces complexity;
- All the ratings are relative to the same base value of 1, which also reduces complexity;
- The information from the ratings is greater than the sum of their constituent performances.

Ultimately, the Comfort Ratings are primarily used to allow the non-expert get an understanding of comfort and so allow the comfort knowledge to be re-used by interested parties other than just comfort experts. Seven Comfort Ratings were created for this research and the sequence in which they are created during a project is shown in Figure A.3. Two of the ratings have different versions depending on the BLC stage. The Project Success Rating has a predicted version at the construction stage and an actual version at the operation stage. The Comfort Rating has six different versions throughout the BLC. The ratings are divided into the three project stages, design, construction and operation. They are sub-divided into Comfort Ratings, whose values are greater than 0 and less than or equal to 1, and Comfort Ratings whose values are greater than 0 and have no upper limit. A description of each and how they are created is given in Table A.3.

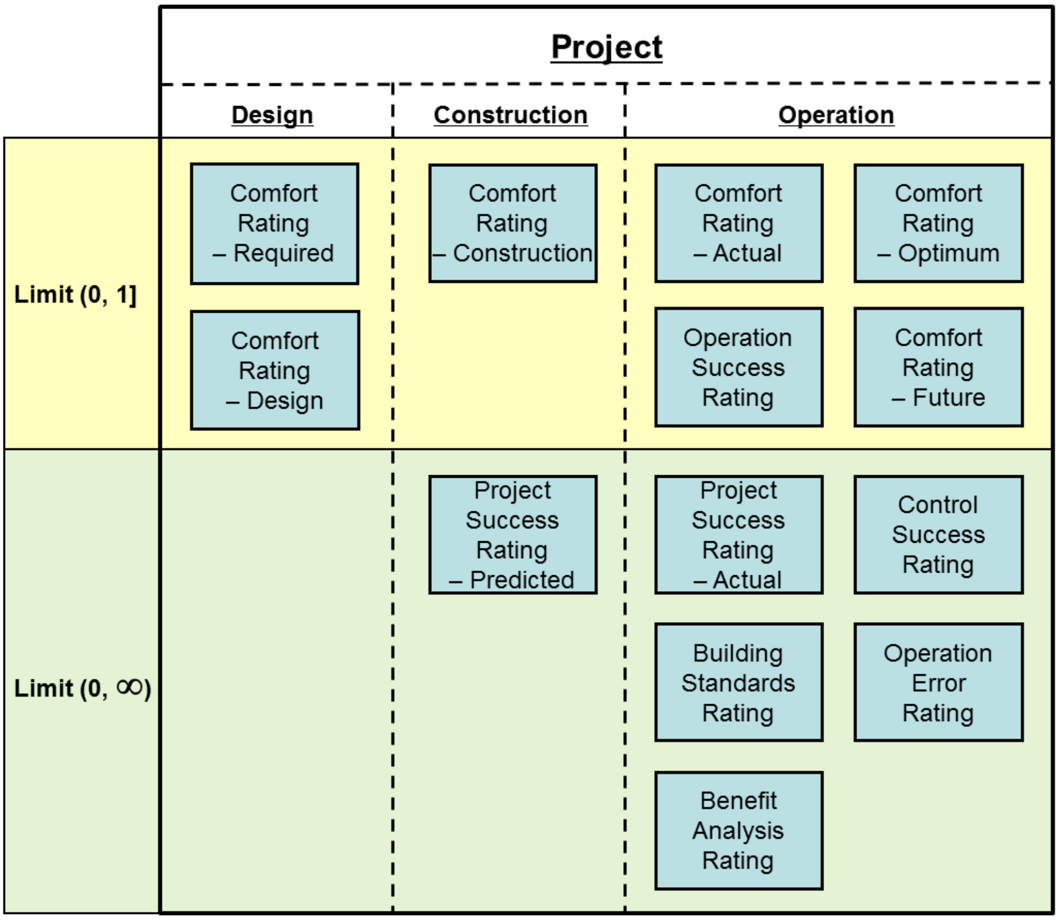

Figure A.3 – Comfort Rating Creation Sequence

Table A.3 – Comfort Ratings Descriptions

Rating	Definition	Dividend Comfort Performance	Divisor Comfort Performance
Comfort Rating – Required (CR-R)	The comfort level required by the building standards.	Ideal	Required
Comfort Rating – Design (CR-D)	How close the Design Comfort Performance is to the Ideal Comfort Performance	Ideal	Design
Comfort Rating – Construction (CR-C)	How close the Construction Comfort Performance is to the Ideal Comfort Performance	Ideal	Construction
Comfort Rating – Actual (CR-A)	How close the Actual Comfort Performance is to the Ideal Comfort Performance	Ideal	Actual
Comfort Rating – Optimum (CR-O)	How close the Optimum Comfort Performance is to the Ideal Comfort Performance	Ideal	Optimum
This table continues on the next page.			

Rating	Definition	Dividend Comfort Performance	Divisor Comfort Performance
This table starts on the previous page.			
Comfort Rating – Future (CR-F)	How close the Future Comfort Performance is to the Ideal Comfort Performance	Ideal	Future
Project Success Rating – Predicted (PSR-P)	The predicted success of the project at achieving the level of comfort predicted by the design.	Design	Optimum
Project Success Rating – Actual (PSR-A)	The actual success of the construction at achieving the level of comfort predicted by the design.	Design	Construction
Operation Success Rating (OSR)	The success of the operation.	Optimum	Actual
Control Success Rating (CrSR)	The accuracy of the Control Comfort Performance at predicting the comfort levels.	Control	Actual
This table continues on the next page.			

Rating	Definition	Dividend Comfort Performance	Divisor Comfort Performance
This table starts on the previous page.			
Building Standards Rating (BSR)	The degree to which the building standards are being complied with.	Required	Actual
Operation Error Rating (OER)	The level of errors in the operation	Historical	Actual
Benefit Analysis Rating (BAR)	The benefit of making the proposed design changes.	Optimum	Future

Comfort Ratings whose values are greater than 0 and less than or equal to 1 can be represented using a Comfort Label similar to the building energy rating (BER). The Comfort Label, as shown in Figure A.4, allows the Comfort Rating to be communicated easily among building stakeholders.

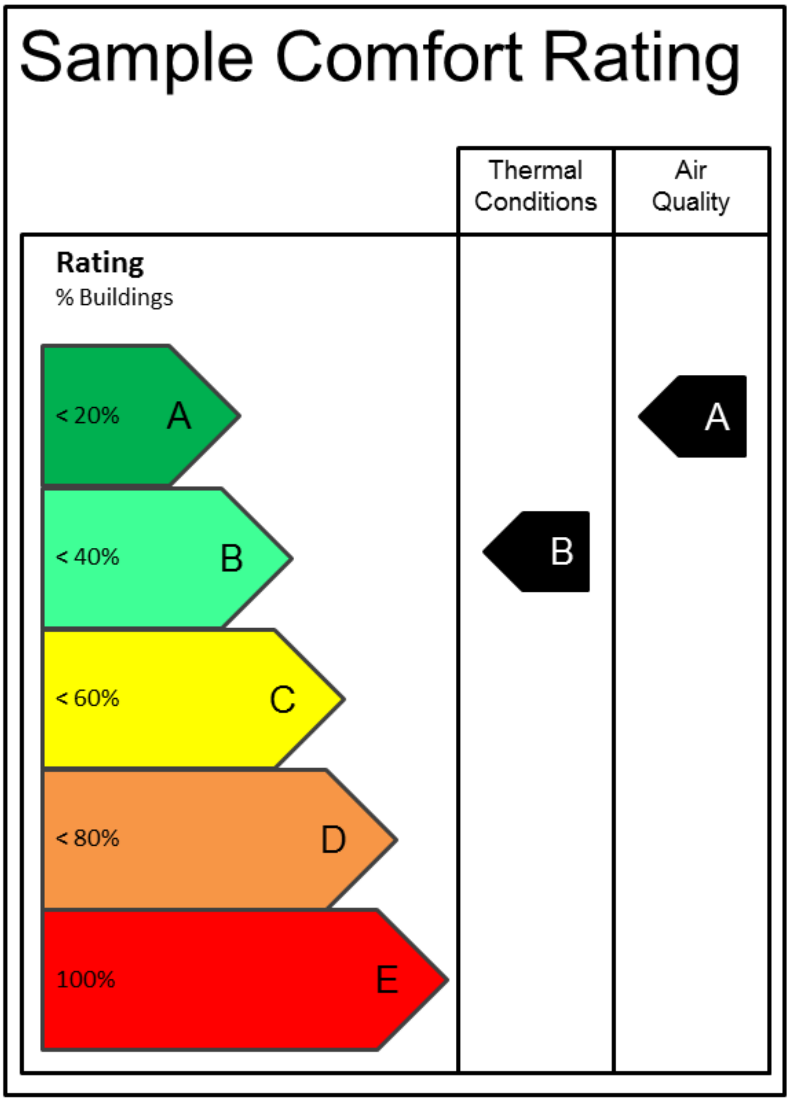

Figure A.4 – Comfort Label

A.3.2.5 Comfort History

The concepts, decisions, and other experiences during a project are a valuable source of knowledge. The Comfort History is created by continuously recording descriptions of the items and activities which affect comfort, storing them in a single location, and linking the recordings with the comfort entity, e.g. a Comfort Performance, that is affected by it. If this information is not stored and made accessible to future project stages and future projects then it is destined to be lost and will have to be recreated when it is required again. An example of this is when an existing heating system is reverse engineered to discover its unrecorded design intent.

A.3.3 Knowledge Storage and Access

ComMet requires that the storage and access format of the comfort knowledge be consistent and unambiguous at all stages of the building life-cycle and that it complies with the BabySteps approach. The knowledge storage must store all the comfort related knowledge, that is the Comfort Performances, the Comfort Ratings, the Comfort History, and all information that was required to create these, such as boundary condition data, simulation model files, etc.

A.4 The LCMS System

A.4.1 LCMS Overview

The LCMS System, as shown in Figure A.5, was developed to support the development and deployment of ComMet. LCMS is a life-cycle comfort monitoring system that is a combination of six components:

- Building Standards;
- Modelling & Simulation;
- Physical Measurement;
- Data Manipulation;
- Information Recording; and
- Knowledge Storage and Access.

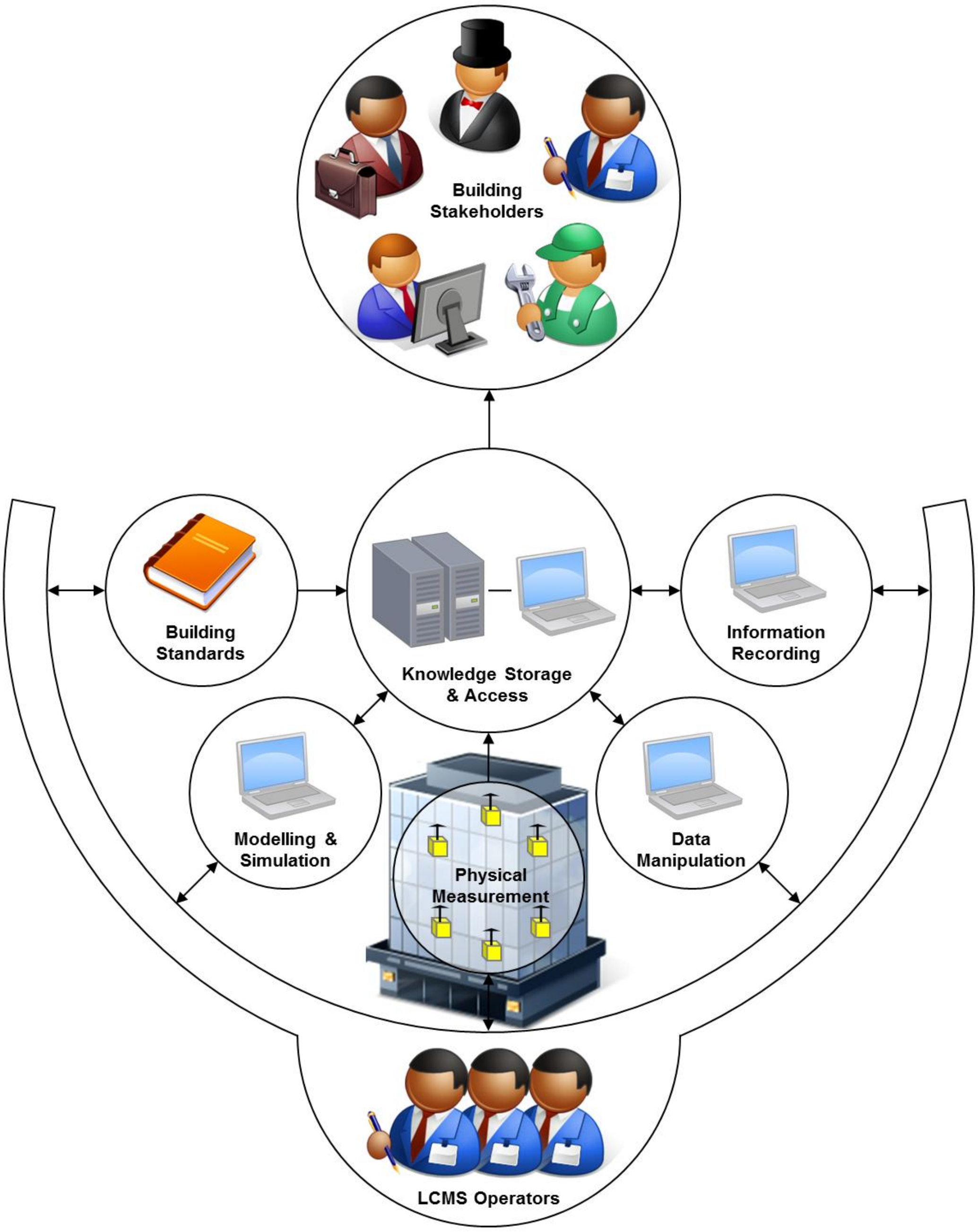

Figure A.5 – The LCMS System

A summary of the ComMet requirements and the LCMS component that fulfils each one is given in Table A.4.

Table A.4 – Summary of ComMet Requirements and their Corresponding LCMS Components

ComMet Requirements	LCMS Component
Comfort Knowledge	
Comfort Performances	
• Building Standards Models	• Building Standards • Data Manipulation
• Simulated Performances	• Modelling & Simulation • Data Manipulation
• Measured Performance	• Physical Measurement • Data Manipulation
Comfort Ratings	Data Manipulation
Comfort History	Information Recording
Knowledge Storage & Access	
Storage System	Knowledge Storage
Access System	Knowledge Access
BabySteps	All Components comply with BabySteps

A.4.2 LCMS Components

A.4.2.1 Building Standards

The Building Standards used in LCMS are the relevant standards for the project which specify the ideal and required conditions for the indoor environment. They provide the information necessary to create the two building standards performances, that is, the Ideal Comfort Performance and Required Comfort Performance, specified by ComMet.

A.4.2.2 Modelling & Simulation

The simulation software is a computational fluid dynamics (CFD) software tool, which can effectively model and simulate the comfort conditions of the indoor environment using the relevant geometry, environmental parameters and boundary conditions. The CFD tool creates the Comfort Model required to generate the seven simulated Comfort Performances specified by ComMet.

CFD is the application of numerical methods to the solution of discrete models of the constituent equations of fluid mechanics [40]. It is used in numerous industries and can also be applied in many areas in building design. CFD is a highly accurate tool, which could, and should, supply very detailed information of the indoor environment during all stages of the building project.

However, CFD is under-utilised in the building sector partly due to a lack of calibration data needed to verify its accuracy. Enabling building specific CFD models to be calibrated will be a big step towards making CFD an effective tool for building design and operation [41]. In this respect, ComMet and CFD are mutually beneficial to each other. CFD provides ComMet with the required simulation models and ComMet provides CFD with the calibration data necessary to verify its models and so make it more useful for the industry.

A.4.2.3 Physical Measurement

The Egg-Whisk Network is a wireless sensor network specifically developed by this research. It consists of a number of wireless Egg-Whisk Motes, as shown in Figure A.6, connected via a dedicated 'Star Network' to a base computer. These motes record the environmental data from the indoor environment required to create the Actual Comfort Performance, and send it back to the base computer. This base computer then accesses the knowledge storage and stores the data. The Egg-Whisk Network has also been used to supply data to a project, which is developing a formal scientific methodology for developing calibrated CFD models of indoor spaces [42].

Wireless sensor networks are ideal for a mobile system that is used in existing operational indoor environments because they are cheap, easy to install, flexible, extendible, compact and portable.

Figure A.6 – The Egg-Whisk Mote

The Egg-Whisk technology is based around the Tyndall modular wireless sensor network prototyping system [43], with application specific sensor layers developed for indoor environment scenarios. The network was developed by the Tyndall National Institute, Ireland[23] and the IRUSE Group in the Department of Civil Engineering, National University of Ireland, Cork and Galway[24].

A.4.2.4 Data Manipulation

The data manipulation is carried out using spreadsheet software, which is a software tool that can edit and run calculations on numerical data stored in a comma separated value (CSV) file. This file format is used to store:

- The measured environmental data from the Egg-Whisk Network;
- The Comfort Performances;
- The Comfort Ratings.

The spreadsheet software is used to create eight Comfort Performances, store the Comfort Performances, and create and store the Comfort Ratings.

A.4.2.5 Information Recording

The information recording is carried out using text editing software, which is a software tool that can create and edit text files. Text files are used to record and store the Comfort History in the central knowledge storage.

[23] www.tyndall.ie
[24] www.iruse.ie

A.4.2.6 Knowledge Storage & Access

The central knowledge storage is a BIM and is used to store all the comfort related knowledge in a standard format as specified by ComMet. The format chosen for this research is the Industry Foundation Classes (IFC)[25]. IFC is designed to facilitate the requirements of numerous construction users including indoor environment designers and operators.

This type of central knowledge storage with a standard data format facilitates the required interoperability as it allows easier transfer of data between all industry disciplines and components [17], [36], [44].

The access is provided by a web-based access system. Having web-based access to the BIM also adds benefits to the system such as reducing costs for the user by reducing hardware and software requirements [36].

A.4.3 Users

All project stakeholders will be potential users of LCMS during the project. These users will use the six components of the LCMS system to capture, store and make available the comfort knowledge as specified by ComMet to enable its re-use in future project stages and future projects.

A.5 Test-Case

A.5.1 Specification

This test-case has three consecutive goals:

- To test the operation of LCMS;
- To show how LCMS implements ComMet;
- To show that ComMet proves the hypothesis.

An existing office room was chosen as the test-case for the new system. It was expected that the results would give an improved understanding of the room and identify areas for improved operation. The geometry was created using IFC compatible software, a graphical representation of which is shown in Figure A.7. This geometry was then stored into the BIM.

[25] www.buildingsmart.com

Figure A.7 – Test-Case Room

A.5.2 Creation of Comfort Performances

The next step in the test-case project was to produce the Comfort Performances. All ten Comfort Performances were created and stored in the BIM. Figure A.8 shows a chart of the Comfort Performances created during the test-case project.

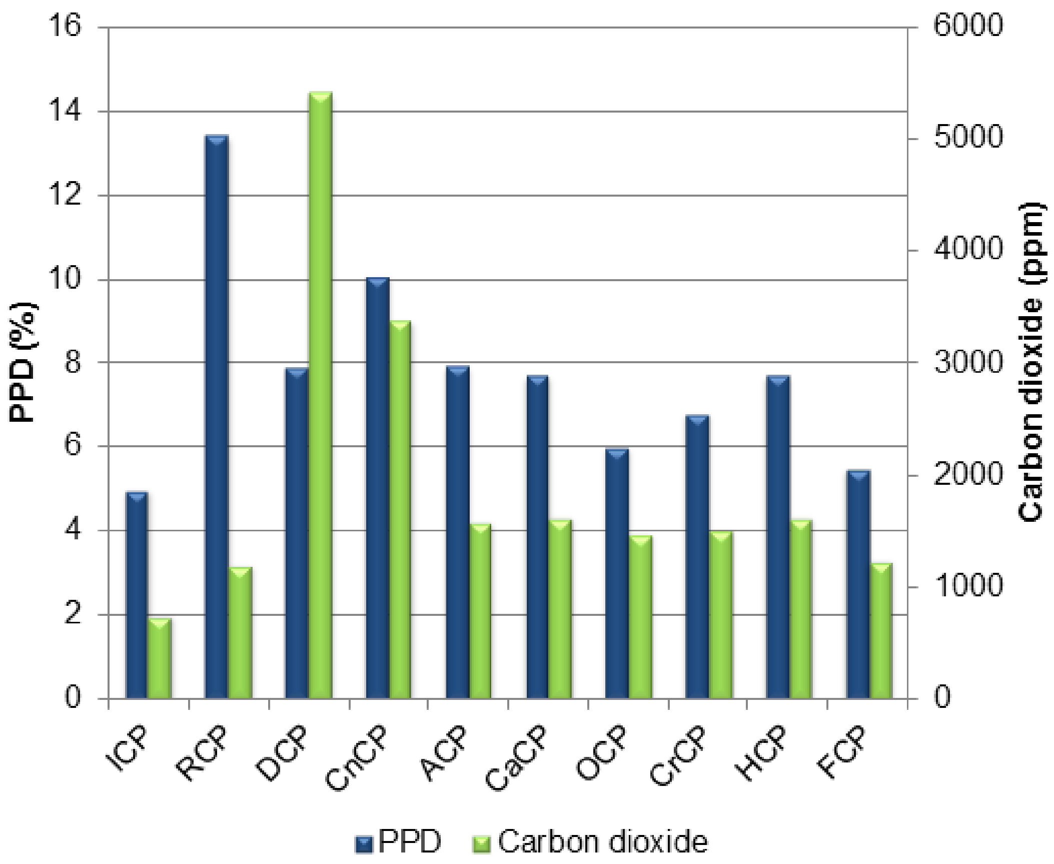

Figure A.8 – Comfort Performances

A.5.3 Creation of Comfort Ratings

As the required performances are produced during the test-case the Comfort Ratings can be also produced and stored. Figure A.9 shows a chart of the Banded Comfort Ratings, those are the Comfort Ratings whose values are greater than 0 and less than or equal to 1 and so can be placed into bands of A to E. Figure A.10 shows a chart of the Non-Banded Comfort Ratings created during the test-case project, those are the Comfort Ratings whose values are greater than 0 and have no upper limit.

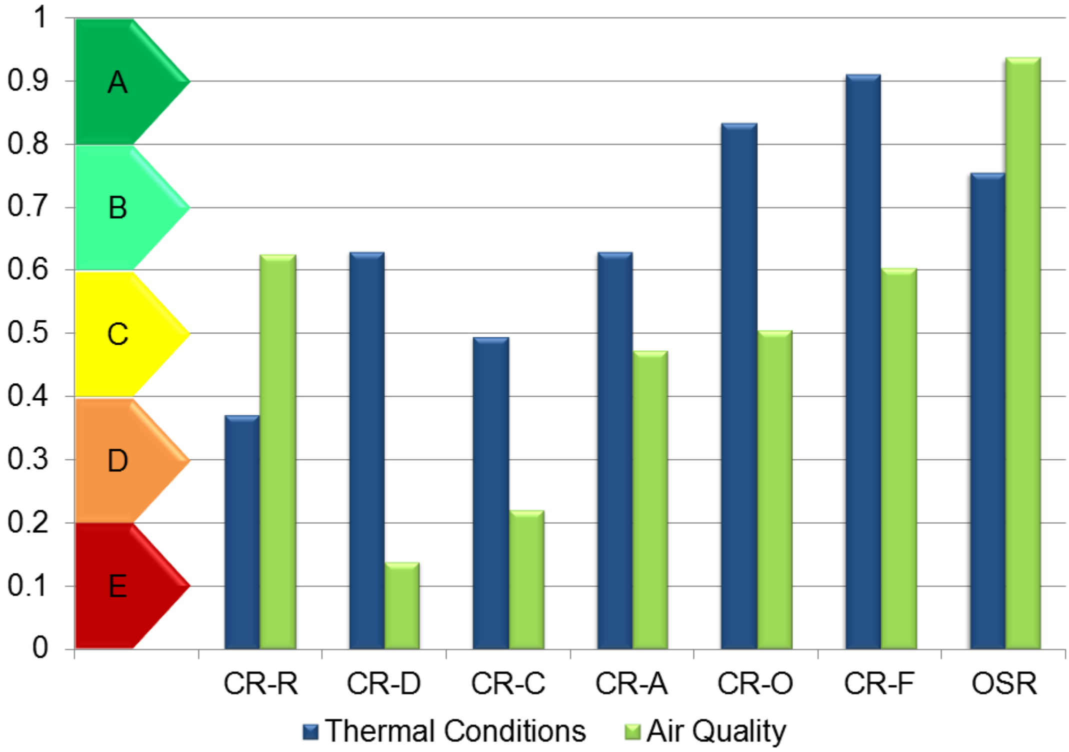

Figure A.9 – Banded Comfort Ratings

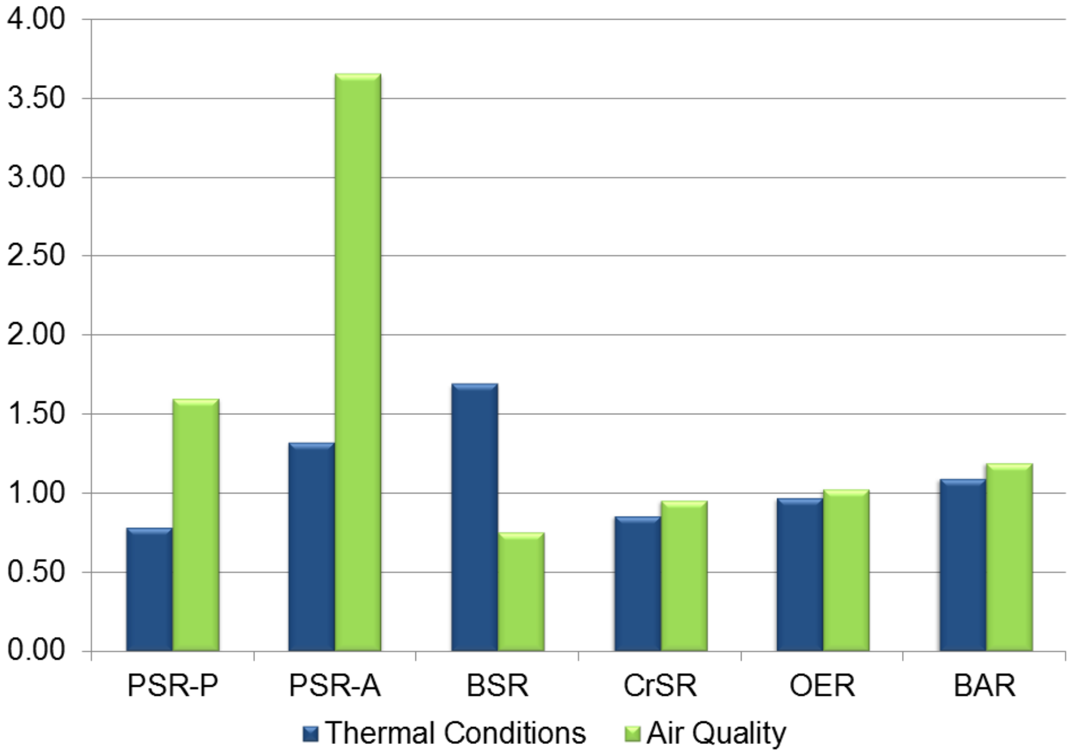

Figure A.10 – Non-Banded Comfort Ratings

A.5.4 Comfort History

The Comfort History is a continuous descriptive record of comfort throughout the project with a focus on what was done, why it was done and what was learned from doing it. Therefore, for the test-case project the Comfort History is, among other items, the reason for choosing particular boundary conditions, input variables, etc., and also the analysis of the performances and ratings as they are produced. As each item was recorded it was stored in the BIM and linked to the relevant comfort entity.

A.5.5 Analysis of the Test-Case

The test-case showed that the LCMS system was able to create, store, and make available the comfort knowledge as specified by the ComMet methodology. This shows that LCMS can operate effectively and also satisfy the requirements of ComMet. The test-case also showed that improved management of the comfort knowledge was possible such as re-using the Comfort Performances generated early in the test-case project to generate Comfort Ratings. These Comfort Ratings were then used to identify options for improved comfort in the room such as the OSR identifying that the operation was not at its optimum. This shows that the ComMet methodology enables comfort knowledge to be managed and that this management of knowledge can improve comfort.

A.6 Conclusion

A.6.1 Proof of Concept

From the review of the current situation and its inefficiencies this research showed that improving the management of comfort knowledge can improve comfort. It deduced that any innovation developed to achieve this should satisfy the BabySteps approach, which was created by this research. BabySteps states that in order to get an innovation adopted into the industry it must be implementable through a number of small changes, but is so far untested.

To improve the management of comfort knowledge, the ComMet methodology was created. ComMet uses Comfort Performances, Comfort

Ratings, and a Comfort History to capture and store knowledge at each stage of a project and make it available to future project stages and future projects. This research created the LCMS system, which implements ComMet through the use of current and emerging technologies, most notably the Egg-Whisk Network that was specially created, by this research, for LCMS. Through a trial use of LCMS it was shown that improving the management of comfort knowledge can improve comfort.

A.6.2 The Future

There is always room for improvement. The ComMet methodology and the LCMS system are no exception to this rule. ComMet will be expanded to include more parameters, such as visual and acoustic conditions, in order to give a more comprehensive definition of comfort. LCMS will be improved by upgrading the Egg-Whisk mote, the BIM and the Web-Based Access.

Outside of the scope of this research, ComMet and LCMS have possible applications. ComMet compliments the current developments in personal preference models for determining comfort and LCMS has a natural application in the future trend towards localised HVAC supply by supplying the required localised measurement.

A.6.3 Maintain Focus

Albert Einstein (physicist) stated that *"Concern for man and his fate must always form the chief interest of all technical endeavours. Never forget this in the midst of your diagrams and equations"*. It is always important to remember the goal of this research. The ultimate purpose of the new approach, principle, methodology, system, and technology, developed by this research is to improve the comfort, health and survival of people.

People are the priority.

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Annex B

Analysis of BIM Proposals

B.1 Introduction

Table B.1 lists the BIM systems analysed by this research. It details the main relevant points, of these systems, in relation to this work.

Table B.1 – Analysis of BIM Proposals

System	Main Relevant Points
ATLAS [1]	• Adoption of interoperability is difficult. • Data from previous projects needs to be re-used as it contains knowledge. • Engineering projects are non-repetitive and different but nevertheless are collections of re-used components. • Proposed getting a set of data models used as a step towards interoperability. • Common format (STEP) data models should be used as the basis for interoperability instead of tool integration. • Tool integration can be achieved using a common data format and data mappers.

BLIS [2]	• Proposed to deliver increasing levels of application interoperability through:
	  ○ semantic model sharing (objects, properties and relationships),
	  ○ implementation collaboration by sub-groups working to support specific BLIS 'views'.
	• Proposed 'jump start' IFC support in shipping applications and IFC based interoperability.
	• Proposed validate any proposed extensions to IFC

	through software implementation.
buildingSMART [3]	• Promotes the connection of the building industry participants that promotes improved information exchange. • Implements coordination of open standards to ensure information flows throughout the lifecycle of the building to all stakeholders. • Develops an infrastructure to advance open industry standards for interoperability and collaboration between practitioners.
COMBI [4]	• Focused on matching and mapping common objects across construction disciplines. • Included project management aspects too like change notifications and communication. • States that change management is the problem with changing different object views.
COMBINE [5]	• Focused on integrating data and design tools. • There are issues defining and encapsulating all building view. • The first phase started in 1992. • Proposed an Operational Integrated Building Design System that could be absorbed into practice. • Proposed field testing. • States the importance of industry involvement. • Proposes using a central database for tool integration.
COMMIT [6]	• Compares construction to automotive and aerospace. • Proposes a new system to integrate and manage documents, data models and applications. • States that interoperability should not be limited to components which have prior knowledge of each other. • An Object Orientated data structure has stronger

	equivalence to the real world than other methodologies: encapsulation, abstraction, and multiple inheritance, are common features in construction. • Project members bring their own, and often different, skills, resources, applications and data formats. • Promotes using existing computer technologies in the construction industry instead of developing new ones. • States that Atlas, Combine, Ratas, and Icon use central project databases. • The current system results in large monolithic programs that try to satisfy a broad range whereas with a common data format a component based approach could be adopted resulting in smaller, more specific, programs.
CONCUR [7]	• A document and IFC test-case for tendering, which uses ProjectWise and ExpressDataModel. • States that organisations follow traditional methods, which results in patchy adoption of new methods.
CONDOR [8]	• Proposes a system to manage other systems. • Chose an incremental and iterative approach. • EDMs treat most documents as blackboxs and cannot edit them. • Main problem is changing the human and organisational culture because they are complex. • Promotes IFC.
CORENET [9]	• States the advantages recognised from IT were, work speed, work quality, communication, speed of sharing, and access to information. • Promotes avoiding technology for the sake of technology, the tech-trap, as it is costly and time consuming and instead deal with current business

	needs not future promises. • Business strategy must support information systems. • Focus on people. • In 2003 35.7% of Singapore companies, in 2000 25% of Swedish, and in 2001 23% of Danish, use EDMs with 12.5% of Danish planning to use it in the following year. • Main problems with IT are the need to continuously upgrade and investment cost is too high. • Develop standards, integrated databases and interactive applications. • Promotes a common language for interoperability. • Promotes local solutions for local businesses as they will deal with the local cultures and systems. • States that for IT to make its quantum leap systems must be re-engineered. • States that the potential needs to be seen to promote interest and investment. • States that the main reasons for IT investment was for more efficient technical work, administrative work, and competitiveness. • The least important reason was to develop new products or business. Users are the priority and they want real benefits.
CoVES [10]	• Centralised management of data
Divercity [11]	• Proposes a completely new system. • Implementation was not giving enough attention in previous proposals. • Promotes the uses of three incremental prototypes with end users tests. • States that human centred, adaptive information systems are needed.

	• States that the current process must be re-designed. • There is a gap between research and users. • Thinks the proposed methodologies are not comprehensive enough. • Uptake is inadequate due to a research issues. • Uses another new process, ‘Requirements Engineering’, to solve the uptake problem.
ECTP-PICT [12]	Promotes ICT in construction.
HITOS [13]	• States that information transfer is costly. • Approx. 5% of construction turnover is spent on defects and deficiencies in Europe and USA. • Information is re-entered up to 7 times before handover. • States the possibility of re-using knowledge in future projects. • Up to 30% of costs may be caused by lack of communication or miscommunication • Uses a database, based on IFC and the Express Data Model, for tool integration.
I3-Con [14]	• The construction industry is fragmented. • Promotes information exchange between building users. • Promotes the integration of building services and IT. • Develops user interfaces to access data models.
ICAtect-II [15]	• Data re-entry encourages large monolithic programs. • Integrating design tools using an Express Data Model. • Software would also be simpler using automatic data upload instead of manual.
ICON [16]	• A method to develop a Computer-Based Information Systems (CBIS) Strategy. • CBIS did not work; there was a mismatch. • Data is the priority one.

	• ICON is an Object Orientated Database developed from models and views. • Information Integration is the main problem • States that existing models should be used first (as far as is possible). • The construction industry is unique partly due to fragmentation.
IFC mBomb [17]	mBomb is a demonstration of an IFC BIM.
IFC Model Server [18]	• Enables the sharing of IFC model data on the Internet by IFC compliant software. • Provides web service APIs that import and export IFC Model data between server and client.
Inpro [19]	• ICT enables productivity growth • States the research results can only be deployed industry wide if all partners of a consortium are able and willing to apply the new methods. • The benefit of an information environment needs to be shared between the contributors e.g. by using generic web-access. • The industry is dominated by SMEs.
ManuBuild [20]	• A proposal for a 'building' factory. • Construction Industry is slow to innovate. • It is a fragmented industry. • It is behind on ICT adoption compared to other industries. • Supports a knowledge based future industry.
OSCON [21]	An IFC BIM with comprehensive integration.
OSMOS [22]	• A high-level management system that can organise and manage other systems e.g. EDM, Email, Data models. • States that changes to the current system must be profitable.

	• The timeline is: Commit -> Condor -> Osmos. • It's a comprehensive system. • States the there is no dominant actor in a project. • This proposed system requires changes and training. • States the unique nature of the construction industry; different firms coming together for a once off project. • Suggests the adoption of new system. • States that construction projects uses temporary and short-term business arrangements. • Uses free software.
RATAS [23]	Provides a timeline for BIM R&D, which is: Racad (1983) -> Ratas (1985) -> Rta (1988) -> TeleRatas (1990) -> Vera (1997) -> ProIT (2002) -> Kitara (2005).
ROADCON [24]	It is a system that facilitates the development of other systems
SPACE [25]	• A complete new system including data model, applications and mappers. • Commercial software upgrades require upgrades of mappers.
Strat-CON [26]	• An open market, evolving businesses and new technology. • Current online EDMs provide basic collaborative tools. • Few organisations exploit project experiences to advance. • Focuses on closing the innovation loop; vision to implementation. • Good report on achieving a vision. • Identified areas for innovation which focused on 'new or improved' systems. • Little research on knowledge re-use in the construction sector.

	• The timeline for this project is: ECTP(2004) -> PICT(FA7)(2005) -> Strat-con(supporting PICT)(2006) • Promotes incremental innovation. Start with the current state, define the vision, and set short, medium and long term implementation goals. • The EU construction sector has 2.3million enterprises, 96% of which have less than 20 people. • The intersection of User Desirability, Technology Feasibility and Business Viability is where innovation makes sense. • Used a strategic implementation action definition template; a proposal page (purposely only one page, i.e. keep it simple) which follows a current state, vision, approach, results, implementation, benefits, and follow-up layout. • Visions, roadmaps and strategic implementation actions.
Wisper [27]	• Used the Java Web Application Interface to do mappings including database to CSV and vice versa. • The web is being transformed from publishing to line-of-business applications. • The power of the web is also under-utilised in the AEC industry. • Used ST-Developer to map the schema to ObjectStore. • A very good technical report on how an IFC web-based system works.

WIMSCI [28]	• Having a system based around a single database would lead to a big problem if the database broke-down.
	• Reasons for lack of change are reluctance, difficulty and cost.
	• Research efforts that relate to ICT in construction are in six areas:
	    o Conceptual framework of web databases,
	    o Electronic Document Management Systems,
	    o Information Analysis,
	    o Web-based Applications,
	    o Reviews and Case Studies,
	    o Application Service Providers, and
	    o Information Standardisation.
	• Data ownership could be a possible issue to central data storage on construction projects.
	• States that the current proposals have limited reliability and efficiency and so haven't indicated clear cost effectiveness.
	• States the construction industry is reluctant to change.
	• The current methods to transfer data are time consuming and expensive e.g. phone, email, meetings, etc.
	• The geographical distance between project members is a hindrance to communicating information.
	• The variation in the project members' specialties and expertise hinders communication.
	• The volume and dissimilarity of data is a hindrance to communication.

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Annex C

PMV and PPD

C.1 Definition

The definition and calculation of the PMV and PPD are given by CIBSE Design Guide A [1]. The PMV combines the influence of environmental factors with personal factors into one value on a thermal sensation scale as shown in Table C.1. The environmental factors are:

- Air temperature;
- Mean radiant temperature;
- Air movement;
- And humidity.

The personal factors are:

- Clothing;
- Activity level.

The PMV is the predicted mean value of the 'votes' of a large group of persons, exposed to the same environment, and with identical clothing and activity.

Table C.1 – Thermal Sensation Scale

Index Value	Thermal Sensation
+ 3	Hot
+ 2	Warm
+ 1	Slightly Warm
0	Neutral
- 1	Slightly Cool
- 2	Cool
- 3	Cold

The predicted mean vote (PMV) is given by the equation:

$$
\begin{aligned}
PMV \quad = \quad & (0.303\, e^{-0.036M} + 0.028)\ \{(M - W) \\
& - 0.00305\ [5733 - 6.99\ (M - W) - p_s] \\
& - 0.42\ [M - W - 58.15] \\
& - (1.7 \times 10^{-5})\ M\ (5867 - p_s) \\
& - 0.0014\ M\ (34 - \theta_{ai}) \\
& - (3.96 \times 10^{-8})\ f_{cl}\ [(\theta_{cl} + 273)^4 \\
& - (\theta_c + 273)^4] - [f_{cl}\ h_c\ (\theta_{cl} - \theta_{ai})]\}
\end{aligned}
\qquad \text{(C.1)}
$$

Where:

- PMV is the predicted mean vote;
- M is metabolic rate ($W \cdot m^{-2}$ of body surface);
- W is external work ($W \cdot m^{-2}$ of body surface) (0 for most activities);
- f_{cl} is the ratio of the area of the clothed human body to that of the unclothed human body;
- θ_{ai} is the average air temperature surrounding the body (°C);
- θ_c is the operative temperature (°C);
- p_s is the partial water vapour pressure in the air surrounding the body (Pa);
- h_c is the convective heat transfer coefficient at the body surface ($W \cdot m^{-2} \cdot K^{-1}$);
- θ_{cl} is the surface temperature of clothing (°C).

The surface temperature of clothing (θ_{cl}) is given by:

$$
\begin{aligned}
\theta_{cl} \quad = \quad & 35.7 - 0.028\ (M - W) - I_{cl}\ \{(3.96 \times 10^{-8}) \\
& \times f_{cl}\ [(\theta_{cl} + 273)4 - (\theta_c + 273)^4] \\
& + f_{cl}\ h_c\ (\theta_{cl} - \theta_{ai})\}
\end{aligned}
\qquad \text{(C.2)}
$$

Where:

I_{cl} is the thermal resistance of clothing ($m^2 \cdot K \cdot W^{-1}$).

For $\{2.38\ (\theta_{cl} - \theta_{ai})^{0.25}\} > 12.1\ \sqrt{v_r}$:

$h_c = 2.38\ (\theta_{cl} - \theta_{ai})^{0.25}$

For $\{2.38\ (\theta_{cl} - \theta_{ai})^{0.25}\} < 12.1\ \sqrt{v_r}$:

$h_c = 12.1\ \sqrt{v_r}$

For $I_{cl} <= 0.078\ m^2 \cdot K \cdot W^{-1}$:

$f_{cl} = 1 + 1.29\ I_{cl}$

For $I_{cl} > 0.078\ m^2 \cdot K \cdot W^{-1}$:

$f_{cl} = 1.05 + 0.645\ I_{cl}$

As the individual thermal sensation votes will be scattered around the mean predicted value (i.e. PMV), it is useful also to predict the percentage of people who would be dissatisfied, taken as those who would vote >+1 or <–1 on the sensation scale. The PPD attempts to do this and it is obtained from the PMV using the following equation:

$$PPD = 100 - 95 \exp[-(0.03353\ PMV^4 + 0.2179\ PMV^2)] \qquad (C.3)$$

C.2 Note

During this research two issues regarding the validity of the above equation were identified. In the CIBSE Guide, 'Design Guide A - Environmental Design', on page 1-35 there is an equation provided for the 'Determination of predicted mean vote (PMV)' and also a 'Computer program for the determination of PMV'. The equation uses the ‘operative temperature’, θ_c (theta c) where the computer program uses the ‘mean radiant temperature’, θ_r (theta r). The equation and computer program are otherwise exactly the same. θ_c and θ_r are related to each other but they are not the same. However, they can have the same value at times.

This could easily have been a revision error but a review of the Ashrae Standard and ISO 7730, which both deal with PMV and are both referenced by Design Guide A confuses the issue further. They both use ‘mean radiant temperature’ in the equation but repeatedly reference ‘operative temperature’ in relation to PMV.

The international standard, ‘ISO 7730 – Ergonomics of the thermal environment – Analytical determination and interpretation of thermal comfort using calculation of the PMV and PPD indices and local thermal comfort criteria’ uses 'mean radiant temperature' instead of ‘operative temperature’ for its calculation of the PMV. This is not unusual as different institutions often use different definitions and calculation methods. The confusing part is, throughout ISO 7730, 'operative temperature' is discussed in reference to

PMV. In fact, Annex E contains 17 pages of tables which relate 'operative temperature' to PMV. Yet, the equation for PMV does not use it.

There were other typographical errors found in ISO 7730 with relation to PMV, which compound the issues regarding the validity of the PMV equation. CIBSE and CEN have been contacted by the author regarding this. They have confirmed that these issues will be investigated. At the publication date of this thesis no further information has been received regarding this issue.

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Annex D

Tyndall25 Mote

D.1 Technical Description

The Tyndall25 Mote [1] is a highly modular, miniaturised wireless sensor platform that addresses the issues of flexibility, power-efficiency and size which are desirable and necessary characteristics for a wireless sensor network platform. The platform was developed as part of the D-Systems project the development of distributed intelligent systems. The hardware platform is analogous to a Lego™-like 25 mm × 25 mm stackable system. Its modular nature lends itself to the development of numerous layers for use in various application scenarios. Layers can be combined in an innovative plug and play fashion and include communication, processing, sensing and power supply layers. The communication layer is comprised of a microcontroller, RF transceiver and integrated antenna. An FPGA layer can be integrated into the system where high-speed DSP processing is required, while various application specific sensors, as well as a generic sensor interface/communications layer have been developed as the sensing layer. The power layer may include batteries or other energy supply/harvesting mechanisms i.e. solar cells or piezo electric power generation mechanisms.

The stackable configuration, as shown in Figure D.1, enables ease of connectivity between layers depending on the system level requirements and deployment scenarios. Modules use a stackable connector system to make the electrical and mechanical interconnections between layers. These high-density connectors have 0.5 mm pitch and are available in a range of interlayer spacing from 5 to 8 mm to allow for various component heights on the PCBs. The connectors facilitate a data bus for configuration and data transfer between module layers. The RF transceiver layer also has a separate 20 pin connector allowing four low noise analogue input channels for integration of sensitive analogue sensors directly to the microcontroller element of this part of the system.

Figure D.1 – Tyndall25 Mote

Additional layers developed include a ZigBee layer, an integration and signal conditioning layer and various sensor layers including an IMU, temperature (I2C/analogue) and light (analogue).

To provide wireless communications capability between sensor nodes, a transceiver/microcontroller layer was developed. This incorporates a microcontroller and transceiver transmitting in the 2.4 GHz ISM band. This layer can be used as a “stand alone” system layer, using the processing power in the microcontroller for system control, communications protocols and limited number crunching capability.

This programmable transceiver has been designed to connect with the separate battery module and FPGA and sensor layers depending on the configuration required by the end user or his mobility/portability requirements. Figure D.2 shows the top and bottom views of the transceiver PCB along with a block diagram showing the interconnection of the main components on the module.

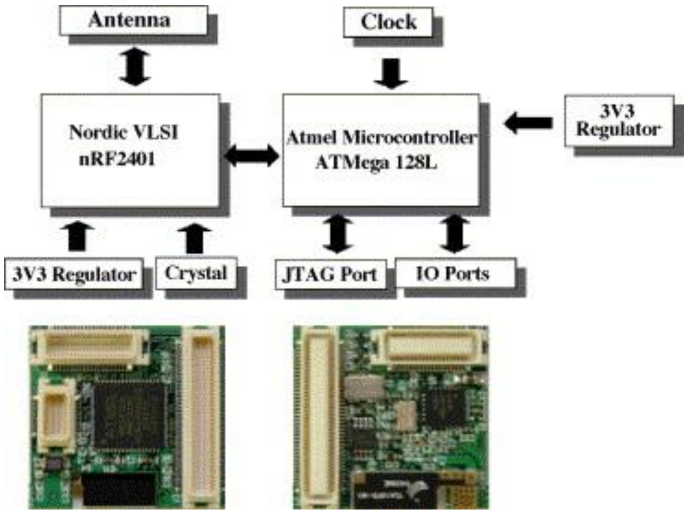

Figure D.2 – Block diagram and final implementation of RF transceiver/microcontroller layer

The transceiver (the nRF2401 from Nordic VLSI) consists of a fully integrated frequency synthesizer, a power amplifier, a crystal oscillator and a modulator. Output power and frequency channels are easily programmable. Current consumption is very low, and a built-in Power Down mode makes power saving easily realizable. The module also features an on board 50 Ω antenna. The embedded microcontroller is based on the ATmega128L, an 8-bit microcontroller with 128 K bytes in system programmable flash. The user can easily program the device with custom protocols for use in his end product or for general product development. TinyOS and is an operating system designed at UC Berkeley engineered to run in hardware platforms with severe resource constraints, and is directly importable into the program memory of this device, thus enabling the development of complex protocols for use in power constrained sensor networks. As the system is envisaged to operate in mobile sensor applications low power consumption of the system is essential. Power consumption considerations were taken into account from the beginning of the design phase of the system. The transceiver selected (nRF2401 from Nordic VLSI) is able to operate in “Shockburst™” mode. This uses on-chip FIFO to clock in data at a low data rate and transmit it at a very high rate thus greatly reducing power consumption. Putting all high-speed signal processing related to RF protocol into the nRF2401 reduces current consumption, lowers system cost (by facilitating the use of a less expensive microcontroller), and greatly reduces the risk of ‘on-air’ collisions due to short (high speed) transmission time. The Atmel microcontroller can be programmed to operate in sleep or powerdown mode awaiting activity on an interrupt pin (i.e. data has arrived, or some alarm condition reached).

D.2 References

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Annex E

CFD Models

E.1 General

The following Sections E.2 – E.8 detail the CFD data used to create the Comfort Performances. It is presented in the form of Comfort Performance Data Sheets.

The Ansys CFD files used to produce the environmental data required to generate the Comfort Performances are stored on the accompanying disc.

The Spreadsheet Software files used to calculate the Comfort Performances and the Comfort Ratings are on the accompanying disc.

E.2 CFD Data for the Design Comfort Performance

DCP Data Sheet		
Input	**Value**	**Justification**
Room Initial Conditions		
Internal		
• Temperature	21°C	Assumed value based on building standards.
• Humidity	40%	Assumed value based on building standards.
• CO_2	450ppm	Assumed value based on building standards and a favourable assumption that the initial CO_2 concentration is only slightly above the outdoor air concentration.
Outside Temperature	4°C	Actual value
People		
Quantity	5 no.	Assumed value based on actual room conditions.
Surface Area	$1.8m^2$	Typical design value
Heat Flux	$65W/m^2$	Typical design value
Respiration		
• Mass Flow Rate	$12m^3/d$	Typical design value

• CO_2	1kg/d	Typical design value
• Moisture	0.5kg/d	Typical design value
Perspiration	0.6kg/d	Typical design value
Computers		
Quantity	5 no.	Assumed value based on actual room conditions.
Surface		
• Area	0.4 m^2	Typical design value
• Heat Flux	58 W/m^2	Typical design value
Vent		
• Mass Flow Rate	0.0128 kg/s	Typical design value
• Temperature	25°C	Typical design value
Monitors		
Quantity	5 no.	Assumed value based on actual room conditions.
Surface Area	0.5 m^2	Typical design value
Heat Flux	71 W/m^2	Typical design value
Lights		
Quantity	4 no.	Actual value
Area	0.3 m^2	Actual value
Heat Flux	387W/m^2	Typical design value

Room Surfaces		
Floor		
• Temperature	16°C	Calculated value based on actual room conditions.
Internal Walls and Ceiling	Adiabatic	Typical design value
External Wall		
• U-Value	0.21 W/m^{2}K	Calculated value based on actual room conditions.
Window Glass		
• U-Value	2.7 W/m^{2}K	Calculated value based on actual room conditions.
Window Wood Panels		
• U-Value	3 W/m^{2}K	Calculated value based on actual room conditions.
Mesh		
Cells		
• Number	403,152	Calculated value
• Minimum Size	50mm	Typical design value
Notes	Refined at edges	Typical design parameter
CFD Details		
Method	Finite Volume	Typical design parameter
Analysis Type	Steady State to Transient	Typical design parameter

Radiation Model	Monte Carlo	Typical design parameter

E.3 CFD Data for the Construction Comfort Performance

The differences between this performance and the DCP are highlighted in red. These are the construction changes as described in Section 5.2.4.1.

CnCP Data Sheet		
Input	**Value**	**Justification**
Room Initial Conditions		
Internal		
• Temperature	21°C	Assumed value based on building standards.
• Humidity	40%	Assumed value based on building standards.
• CO_2	450ppm	Assumed value based on building standards and a favourable assumption that the initial CO_2 concentration is only slightly above the outdoor air concentration.
Outside Temperature	4°C	Actual value
People		
Quantity	5 no.	Assumed value based on actual room conditions.
Surface Area	1.8m^2	Typical design value
Heat Flux	65W/m^2	Typical design value

Respiration		
• Mass Flow Rate	$12m^3/d$	Typical design value
• CO_2	1kg/d	Typical design value
• Moisture	0.5kg/d	Typical design value
Perspiration	0.6kg/d	Typical design value
Computers		
Quantity	5 no.	Assumed value based on actual room conditions.
Surface		
• Area	$0.4\ m^2$	Typical design value
• Heat Flux	$58\ W/m^2$	Typical design value
Vent		
• Mass Flow Rate	0.0128 kg/s	Typical design value
• Temperature	25°C	Typical design value
Monitors		
Quantity	5 no.	Assumed value based on actual room conditions.
Surface Area	$0.5\ m^2$	Typical design value
Heat Flux	$71\ W/m^2$	Typical design value
Lights		
Quantity	4 no.	Actual value
Area	$0.3\ m^2$	Actual value

Heat Flux	387W/m^2	Typical design value
Room Surfaces		
Floor		
• Temperature	16°C	Calculated value based on actual room conditions.
Internal Walls and Ceiling	Adiabatic	Typical design value
External Wall		
• U-Value	0.21 W/m^{2}K	Calculated value based on actual room conditions.
Window Glass		
• U-Value	2.7 W/m^{2}K	Calculated value based on actual room conditions.
Window Wood Panels		
• U-Value	3 W/m^{2}K	Calculated value based on actual room conditions.
Unsealed Pipe Openings		
Quantity	2 no.	Actual Value
Area	0.1725 m^2	Actual Value
Boundary Type	Opening	Actual Value
Relative Pressure	0 Pa	Assumed value based on actual room conditions.
Temperature	21°C	Assumed value based on building standards.
Humidity	40%	Assumed value based on

		building standards.
CO_2	450ppm	Assumed value based on building standards and a favourable assumption that the initial CO_2 concentration is only slightly above the outdoor air concentration.
Mesh		
Cells		
• Number	403,152	Calculated value
• Minimum Size	50mm	Typical design value
Notes	Refined at edges	Typical design parameter
CFD Details		
Method	Finite Volume	Typical design parameter
Analysis Type	Steady State to Transient	Typical design parameter
Radiation Model	Monte Carlo	Typical design parameter

E.4 CFD Data for the Calibrated Comfort Performance

The differences between this performance and the CnCP are highlighted in red.

CaCP Data Sheet		
Input	**Value**	**Justification**
Room Initial Conditions		
Internal		
• Temperature	21°C	Assumed value based on building standards.
• Humidity	40%	Assumed value based on building standards.
• CO_2	450ppm	Assumed value based on building standards and a favourable assumption that the initial CO_2 concentration is only slightly above the outdoor air concentration.
Outside Temperature	4°C	Actual value
People		
Quantity	5 no.	Assumed value based on actual room conditions.
Surface Area	1.8m^2	Typical design value
Heat Flux	65W/m^2	Typical design value

Respiration		
• Mass Flow Rate	$12 m^3/d$	Typical design value
• CO_2	1kg/d	Typical design value
• Moisture	0.5kg/d	Typical design value
Perspiration	0.6kg/d	Typical design value
Computers	**None**	Actual value
Monitors	**None**	Actual value
Radiators		
Quantity	2 no.	Actual value
Surface		
• Area	$0.6 m^2$	Actual value
• Heat Flux	$72 W/m^2$	Calculated value based on radiator specifications and actual room conditions.
Vent		
• Mass Flow Rate	0.075 kg/s	Calculated value based on radiator specifications and actual room conditions.
• Temperature	34.9°C	Calculated value based on radiator specifications and actual room conditions.
Laptops		

Quantity	5 no.	Actual value
Surface Area	0.5 m^2	Typical design value
Heat Flux	55 W/m^2	Typical design value
Lights		
Quantity	4 no.	Actual value
Area	0.3 m^2	Actual value
Heat Flux	387W/m^2	Typical design value
Room Surfaces		
Floor		
• Temperature	16°C	Calculated value based on actual room conditions.
Internal Walls and Ceiling	Adiabatic	Typical design value
External Wall		
• U-Value	0.21 W/m^2K	Calculated value based on actual room conditions.
Window Glass		
• U-Value	2.7 W/m^2K	Calculated value based on actual room conditions.
Window Wood Panels		
• U-Value	3 W/m^2K	Calculated value based on actual room conditions.
Unsealed Pipe Openings		

Quantity	2 no.	Actual Value
Area	0.1725 m^2	Actual Value
Boundary Type	Opening	Actual Value
Relative Pressure	0 Pa	Assumed value based on actual room conditions.
Temperature	21°C	Assumed value based on building standards.
Humidity	40%	Assumed value based on building standards.
CO_2	450ppm	Assumed value based on building standards and a favourable assumption that the initial CO_2 concentration is only slightly above the outdoor air concentration.
Air Leak Gap at Door		
Area	0.28 m^2	Calculated value based on actual room conditions.
Boundary Type	Opening	Actual Value
Relative Pressure	0 Pa	Assumed value based on actual room conditions.
Temperature	21°C	Assumed value based on building standards.
Humidity	40%	Assumed value based on building standards.
CO_2	450ppm	Assumed value based on building standards and a

		favourable assumption that the initial CO_2 concentration is only slightly above the outdoor air concentration.
Mesh		
Cells		
• Number	403,152	Calculated value
• Minimum Size	50mm	Typical design value
Notes	Refined at edges	Typical design parameter
CFD Details		
Method	Finite Volume	Typical design parameter
Analysis Type	Steady State to Transient	Typical design parameter
Radiation Model	Monte Carlo	Typical design parameter

E.5 CFD Data for the Optimum Comfort Performance

The differences between this performance and the CaCP are highlighted in red.

OCP Data Sheet		
Input	**Value**	**Justification**
Room Initial Conditions		
Internal		
• Temperature	21°C	Assumed value based on building standards.
• Humidity	40%	Assumed value based on building standards.
• CO_2	450ppm	Assumed value based on building standards and a favourable assumption that the initial CO_2 concentration is only slightly above the outdoor air concentration.
Outside Temperature	4°C	Actual value
People		
Quantity	5 no.	Assumed value based on actual room conditions.
Surface Area	1.8m^2	Typical design value
Heat Flux	65W/m^2	Typical design value

Respiration		
• Mass Flow Rate	$12m^3/d$	Typical design value
• CO_2	1kg/d	Typical design value
• Moisture	0.5kg/d	Typical design value
Perspiration	0.6kg/d	Typical design value
Radiators		
Quantity	2 no.	Actual value
Surface		
• Area	$0.6\ m^2$	Actual value
• Heat Flux	$72\ W/m^2$	Calculated value based on radiator specifications and actual room conditions.
Vent		
• Mass Flow Rate	0.075 kg/s	Calculated value based on radiator specifications and actual room conditions.
• Temperature	34.9°C	Calculated value based on radiator specifications and actual room conditions.
Laptops		
Quantity	5 no.	Actual value
Surface Area	$0.5\ m^2$	Typical design value
Heat Flux	$55\ W/m^2$	Typical design value

Lights		
Quantity	4 no.	Actual value
Area	0.3 m^2	Actual value
Heat Flux	387W/m^2	Typical design value
Room Surfaces		
Floor		
• Temperature	17°C	Calculated value using optimum control strategy.
Internal Walls and Ceiling	Adiabatic	Typical design value
External Wall		
• U-Value	0.21 W/m^2K	Calculated value based on actual room conditions.
Window Glass		
• U-Value	2.7 W/m^2K	Calculated value based on actual room conditions.
Window Wood Panels		
• U-Value	3 W/m^2K	Calculated value based on actual room conditions.
Unsealed Pipe Openings		
Quantity	2 no.	Actual Value
Area	0.1725 m^2	Actual Value
Boundary Type	Opening	Actual Value
Relative Pressure	0 Pa	Assumed value based on actual room conditions.

Temperature	21°C	Assumed value based on building standards.
Humidity	40%	Assumed value based on building standards.
CO_2	450ppm	Assumed value based on building standards and a favourable assumption that the initial CO_2 concentration is only slightly above the outdoor air concentration.
Air Leak Gap at Door		
Area	0.28 m^2	Calculated value based on actual room conditions.
Boundary Type	Opening	Actual Value
Relative Pressure	0 Pa	Assumed value based on actual room conditions.
Temperature	21°C	Assumed value based on building standards.
Humidity	40%	Assumed value based on building standards.
CO_2	450ppm	Assumed value based on building standards and a favourable assumption that the initial CO_2 concentration is only slightly above the outdoor air concentration.

Mesh		
Cells		
• Number	403,152	Calculated value
• Minimum Size	50mm	Typical design value
Notes	Refined at edges	Typical design parameter
CFD Details		
Method	Finite Volume	Typical design parameter
Analysis Type	Steady State to Transient	Typical design parameter
Radiation Model	Monte Carlo	Typical design parameter

E.6 CFD Data for the Control Comfort Performance

The differences between this performance and the CaCP are highlighted in red.

CrCP Data Sheet		
Input	**Value**	**Justification**
Room Initial Conditions		
Internal		
• Temperature	21°C	Assumed value based on building standards.
• Humidity	40%	Assumed value based on building standards.
• CO_2	450ppm	Assumed value based on building standards and a favourable assumption that the initial CO_2 concentration is only slightly above the outdoor air concentration.
Outside Temperature	6°C	Arbitrarily chosen value to demonstrate the Control Comfort Performance.
People		
Quantity	5 no.	Assumed value based on actual room conditions.
Surface Area	1.8m^2	Typical design value

Heat Flux	65W/m^2	Typical design value
Respiration		
• Mass Flow Rate	12m^3/d	Typical design value
• CO_2	1kg/d	Typical design value
• Moisture	0.5kg/d	Typical design value
Perspiration	0.6kg/d	Typical design value
Radiators		
Quantity	2 no.	Actual value
Surface		
• Area	0.6 m^2	Actual value
• Heat Flux	72 W/m^2	Calculated value based on radiator specifications and actual room conditions.
Vent		
• Mass Flow Rate	0.075 kg/s	Calculated value based on radiator specifications and actual room conditions.
• Temperature	34.9°C	Calculated value based on radiator specifications and actual room conditions.
Laptops		
Quantity	5 no.	Actual value
Surface Area	0.5 m^2	Typical design value
Heat Flux	55 W/m^2	Typical design value

Lights		
Quantity	4 no.	Actual value
Area	0.3 m^2	Actual value
Heat Flux	387W/m^2	Typical design value
Room Surfaces		
Floor		
• Temperature	16°C	Calculated value using optimum control strategy.
Internal Walls and Ceiling	Adiabatic	Typical design value
External Wall		
• U-Value	0.21 W/m^2K	Calculated value based on actual room conditions.
Window Glass		
• U-Value	2.7 W/m^2K	Calculated value based on actual room conditions.
Window Wood Panels		
• U-Value	3 W/m^2K	Calculated value based on actual room conditions.
Unsealed Pipe Openings		
Quantity	2 no.	Actual Value
Area	0.1725 m^2	Actual Value
Boundary Type	Opening	Actual Value

Relative Pressure	0 Pa	Assumed value based on actual room conditions.
Temperature	21°C	Assumed value based on building standards.
Humidity	40%	Assumed value based on building standards.
CO_2	450ppm	Assumed value based on building standards and a favourable assumption that the initial CO_2 concentration is only slightly above the outdoor air concentration.
Air Leak Gap at Door		
Area	0.28 m^2	Calculated value based on actual room conditions.
Boundary Type	Opening	Actual Value
Relative Pressure	0 Pa	Assumed value based on actual room conditions.
Temperature	21°C	Assumed value based on building standards.
Humidity	40%	Assumed value based on building standards.
CO_2	450ppm	Assumed value based on building standards and a favourable assumption that the initial CO_2 concentration is only slightly above the outdoor air concentration.

Mesh		
Cells		
• Number	403,152	Calculated value
• Minimum Size	50mm	Typical design value
Notes	Refined at edges	Typical design parameter
CFD Details		
Method	Finite Volume	Typical design parameter
Analysis Type	Steady State to Transient	Typical design parameter
Radiation Model	Monte Carlo	Typical design parameter

E.7 CFD Data for the Historical Comfort Performance

Since the HCP is the Comfort Model adjusted to use the control strategy employed on the day of the ACP, and since, in this case, the Comfort Model is calibrated using the same ACP, the HCP and CaCP in this case are identical.

HCP Data Sheet		
Input	**Value**	**Justification**
Room Initial Conditions		
Internal		
• Temperature	21°C	Assumed value based on building standards.
• Humidity	40%	Assumed value based on building standards.
• CO_2	450ppm	Assumed value based on building standards and a favourable assumption that the initial CO_2 concentration is only slightly above the outdoor air concentration.
Outside Temperature	4°C	Actual value
People		
Quantity	5 no.	Assumed value based on actual room conditions.
Surface Area	$1.8m^2$	Typical design value

Heat Flux	65W/m^2	Typical design value
Respiration		
• Mass Flow Rate	12m^3/d	Typical design value
• CO_2	1kg/d	Typical design value
• Moisture	0.5kg/d	Typical design value
Perspiration	0.6kg/d	Typical design value
Radiators		
Quantity	2 no.	Actual value
Surface		
• Area	0.6 m^2	Actual value
• Heat Flux	72 W/m^2	Calculated value based on radiator specifications and actual room conditions.
Vent		
• Mass Flow Rate	0.075 kg/s	Calculated value based on radiator specifications and actual room conditions.
• Temperature	34.9°C	Calculated value based on radiator specifications and actual room conditions.
Laptops		
Quantity	5 no.	Actual value
Surface Area	0.5 m^2	Typical design value
Heat Flux	55 W/m^2	Typical design value

Lights		
Quantity	4 no.	Actual value
Area	0.3 m^2	Actual value
Heat Flux	387W/m^2	Typical design value
Room Surfaces		
Floor		
• Temperature	16°C	Calculated value based on actual room conditions.
Internal Walls and Ceiling	Adiabatic	Typical design value
External Wall		
• U-Value	0.21 W/m^2K	Calculated value based on actual room conditions.
Window Glass		
• U-Value	2.7 W/m^2K	Calculated value based on actual room conditions.
Window Wood Panels		
• U-Value	3 W/m^2K	Calculated value based on actual room conditions.
Unsealed Pipe Openings		
Quantity	2 no.	Actual Value
Area	0.1725 m^2	Actual Value
Boundary Type	Opening	Actual Value

Relative Pressure	0 Pa	Assumed value based on actual room conditions.
Temperature	21°C	Assumed value based on building standards.
Humidity	40%	Assumed value based on building standards.
CO_2	450ppm	Assumed value based on building standards and a favourable assumption that the initial CO_2 concentration is only slightly above the outdoor air concentration.
Air Leak Gap at Door		
Area	0.28 m^2	Calculated value based on actual room conditions.
Boundary Type	Opening	Actual Value
Relative Pressure	0 Pa	Assumed value based on actual room conditions.
Temperature	21°C	Assumed value based on building standards.
Humidity	40%	Assumed value based on building standards.
CO_2	450ppm	Assumed value based on building standards and a favourable assumption that the initial CO_2 concentration is only slightly above the outdoor air concentration.

Mesh		
Cells		
• Number	403,152	Calculated value
• Minimum Size	50mm	Typical design value
Notes	Refined at edges	Typical design parameter
CFD Details		
Method	Finite Volume	Typical design parameter
Analysis Type	Steady State to Transient	Typical design parameter
Radiation Model	Monte Carlo	Typical design parameter

E.8 CFD Data for the Future Comfort Performance

The differences between this performance and the CaCP are highlighted in red.

HCP Data Sheet		
Input	**Value**	**Justification**
Room Initial Conditions		
Internal		
• Temperature	21°C	Assumed value based on building standards.
• Humidity	40%	Assumed value based on building standards.
• CO_2	450ppm	Assumed value based on building standards and a favourable assumption that the initial CO_2 concentration is only slightly above the outdoor air concentration.
Outside Temperature	4°C	Actual value
People		
Quantity	5 no.	Assumed value based on actual room conditions.
Surface Area	$1.8m^2$	Typical design value
Heat Flux	$65W/m^2$	Typical design value

Respiration		
• Mass Flow Rate	12m^3/d	Typical design value
• CO_2	1kg/d	Typical design value
• Moisture	0.5kg/d	Typical design value
Perspiration	0.6kg/d	Typical design value
Radiators		
Quantity	2 no.	Actual value
Surface		
• Area	0.6 m^2	Actual value
• Heat Flux	72 W/m^2	Calculated value based on radiator specifications and actual room conditions.
Vent		
• Mass Flow Rate	0.075 kg/s	Calculated value based on radiator specifications and actual room conditions.
• Temperature	34.9°C	Calculated value based on radiator specifications and actual room conditions.
Laptops		
Quantity	5 no.	Actual value
Surface Area	0.5 m^2	Typical design value
Heat Flux	55 W/m^2	Typical design value

Lights		
Quantity	4 no.	Actual value
Area	0.3 m^2	Actual value
Heat Flux	387W/m^2	Typical design value
Room Surfaces		
Floor		
• Temperature	17°C	Chosen value to improve the comfort of the room.
Internal Walls and Ceiling	Adiabatic	Typical design value
External Wall		
• U-Value	0.21 W/m^2K	Calculated value based on actual room conditions.
Window Glass		
• U-Value	2.7 W/m^2K	Calculated value based on actual room conditions.
Window Wood Panels		
• U-Value	3 W/m^2K	Calculated value based on actual room conditions.
Unsealed Pipe Openings		
Quantity	2 no.	Actual Value
Area	0.1725 m^2	Actual Value
Boundary Type	Opening	Actual Value
Relative Pressure	0 Pa	Assumed value based on actual room conditions.

Temperature	21°C	Assumed value based on building standards.
Humidity	40%	Assumed value based on building standards.
CO_2	450ppm	Assumed value based on building standards and a favourable assumption that the initial CO_2 concentration is only slightly above the outdoor air concentration.
Air Leak Gap at Door		
Area	0.28 m^2	Calculated value based on actual room conditions.
Boundary Type	Opening	Actual Value
Relative Pressure	0 Pa	Assumed value based on actual room conditions.
Temperature	21°C	Assumed value based on building standards.
Humidity	40%	Assumed value based on building standards.
CO_2	450 ppm	Assumed value based on building standards and a favourable assumption that the initial CO_2 concentration is only slightly above the outdoor air concentration.

Inlets		
Quantity	2 no.	Chosen value to improve the comfort of the room.
Area	0.24 m^2	Chosen value to improve the comfort of the room.
Boundary Type	Inlet	Chosen value to improve the comfort of the room.
Air Speed	0.3 m/s	Chosen value to improve the comfort of the room.
Temperature	23°C	Chosen value to improve the comfort of the room.
Humidity	40%	Chosen value to improve the comfort of the room.
CO_2	450 ppm	Chosen value to improve the comfort of the room.
Extract		
Area	0.48 m^2	Chosen value to improve the comfort of the room.
Boundary Type	Extract	Chosen value to improve the comfort of the room.
Air Speed	0.5 m/s	Chosen value to improve the comfort of the room.
Mesh		
Cells		
• Number	403,152	Calculated value

• Minimum Size	50mm	Typical design value
Notes **CFD Details**	Refined at edges	Typical design parameter
Method	Finite Volume	Typical design parameter
Analysis Type	Steady State to Transient	Typical design parameter
Radiation Model	Monte Carlo	Typical design parameter