EMBEDDING INTEGRATED BUILDING PERFORMANCE ASSESSMENT IN DESIGN PRACTICE

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Embedding Integrated Building Performance Assessment in Design Practice

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FOREWORD

Context

The work reported in the thesis was undertaken over a period of around 16 years and at the commencement of the work, designers were not in the habit of using computers, let alone computer calculation and simulation techniques. Similarly, the tools that did exist were almost exclusively mono-variate, and the notion of integrated assessment was no more than a pipe dream.

Computer simulation of buildings was an activity confined to architectural, building physics and engineering research labs. However, for a variety of reasons – the 1970s energy crisis, advances in materials, imported design ambitions, for example, there was an emerging interest in the potential of computer simulation from within the more progressive design practices – but no knowledge of tools or how to use them.

The context within which the work took place was a constantly evolving one and therefore the research methods had to be adjusted as other things changed (e.g. desirable became regulation; PCs began to emerge within design offices; workstation power advantages over PCs diminished; CAD tools emerged and so on).

Research Method

The research method conjectured and tested solutions to the adoption of simulation as a routine activity within the real world, quantifying the outcomes in terms of measured energy and environmental benefits, while protecting the professions from the barriers caused by the time pressures of the design process, a lack of trust in new methods and the cost and time required to adopt new methods.

The work was undertaken in two phases over sixteen years, from 1987 to 2004 and is reported chronologically.

At the start of the work, the author was fortunate to be employed as a researcher first with the University of Strathclyde's Architecture and Building Aids Computer Unit (ABACUS) where she had the opportunity to take on the role of principal investigator on a government funded technology transfer initiative – the Energy Design Advisory Service – until 1998. The research facilitated access to simulation through specialists working on behalf of design teams, in parallel with the day-to-day practices of the design process. The objective was to evaluate the appetite for simulation in practice without interfering with the business of designing buildings.

The first phase concluded that there was sufficient enthusiasm from design teams to pursue a second phase, whereby support was provided to assist energy sector companies to move simulation skills into their companies, while minimising disruption to the design process. The research was undertaken while employed as a researcher with the Energy Systems Research Unit (ESRU) on another government funded initiative, the Scottish Energy Systems Group (SESG), which focused on embedding integrated performance assessment in design practice. The work phases are summarised in figure A.

Unusually, if not uniquely, this provided the author with access to over 1500 projects and around 700 designers and design teams working real time on live building projects over a period of ten or eleven years with EDAS, followed by a more targeted approach through an industry club of around 40 member companies from 1999 - 2004.

The Research

The work has three main elements:

1. At the commencement of the work, it was true to say that despite the ability to produce innovative buildings, the construction industry was conservative in terms of the procedures it employed, and on investigation, notwithstanding the adoption of the metric system, little else had changed in terms of approach to design methods since the 1930s. As a result of this, initially the research work focused on the up-skilling of the professions in terms of building an understanding of the issues of the day.

   In order to complement access to modelling through recognised experts, conventional knowledge transfer methods such as best practice advice, EU publications, case studies, guides and advice notes were employed alongside CPD seminars and focus group discussions.

   This had a high impact initially but the willingness to engage at this level diminished as the industry's knowledge plateaued. The conclusion drawn was that the industry had reached a level of understanding of the key issues, but that practitioners still lacked the necessary skills to undertake simulation as an in-house activity.

2. The next stage of the research was prompted by the outcome of the first, which pointed to the need for other, more advanced mechanisms to engage the professions. It was as yet unclear whether or not designers felt that raising their general level of emerging design issues was adequate enough to allow them to interact with simulations specialists. In addition, the industry's appetite for simulation - either as a supported or an in-house activity had yet to be fully tested. This appetite and the potential environmental savings were observed and quantified during this phase of research.

   The outcome of the research to that point was that the professions in Scotland were now ready to embed simulation in practice – if not yet confident about managing the process. This was prompted by a number of observations - including the fact that the associated time delay between commissioning an expert and testing out a second or third design hypothesis increasingly caused frustration, whereas it was initially seen as part of the process. In addition some if not all of the traditional barriers were receding – such as the introduction of increasingly powerful and accessibly priced desktop computers.

3. The final phase of the research developed, tested and observed the impact of traditional and novel support mechanisms to facilitate the move of simulation from an academic or specialist domain, reserved for flagship projects to a point whereby it is in every day use within the design process on ordinary projects.

Key elements of this were developing a better understanding of the barriers to use in practice and testing supported solutions while assisting the development of mechanisms to facilitate use in practice in the longer term. This revealed an appetite for integrated performance assessment which brought with it a whole new set of issues relating to Simulation Methodologies and Performance Assessment Methods, Management issues and the need for QA.

Hypothesis

The research method entailed working directly with practitioners to identify and analyse barriers to the routine use of simulation tools in practice. The underlying hypothesis is that simulation can provide answers to design problems quicker, cheaper and better than conventional tools, provided the appropriate mechanisms exist to support users. The thesis reports all of this as researched and observed over time.

Outcomes

The key outcomes are contributions in the following areas (as summarised in figure B):

1. Understanding the barriers to tool use in practice and helping the professions to overcome these. This work was undertaken through observational research into the use of simulation in practice over 20 years.

2. Contributions to development of quality assurance procedures for use in practice. Quality assurance was the single biggest issue outside of the technical competencies of models at the start of the research. The industry would not adopt a simulation approach to design if it could not assure the quality of the advice given on the basis

of the results. Quality assurance procedures were developed to observe, document and improve the process. The research makes two contributions in this regard:

a. The development of quality assurance procedures for selecting consultants and for managing the process of the consultant/ customer relationship.
b. Assistance with the development of appropriate quality assurance procedures for the application of simulation methodologies and procedures in practice.

3. In support of QA a Performance Assessment Method or PAM can further support simulation use in design practice by directing the user's line of inquiry. The research contributes to the development of simulation performance assessment methods and procedures by identifying industry needs and issues associated with use by practitioners and feeding this back to researchers in the field to better inform new application methods in terms of who does what, why, when and where - working as conduit between industry and companies – which allowed information flow in two directions.

4. The fourth contribution is to the ongoing development of integrated performance views (IPVs) for practitioner and client use. Prior to the advent of integrated tools practitioners were already recognising the need to compare and contrast results from different modelling assessment programs – e.g. lighting and thermal, impact on energy consumption of renewable integration and risk of glare associated with daylight use, for example.

Figure A – Phases of the research

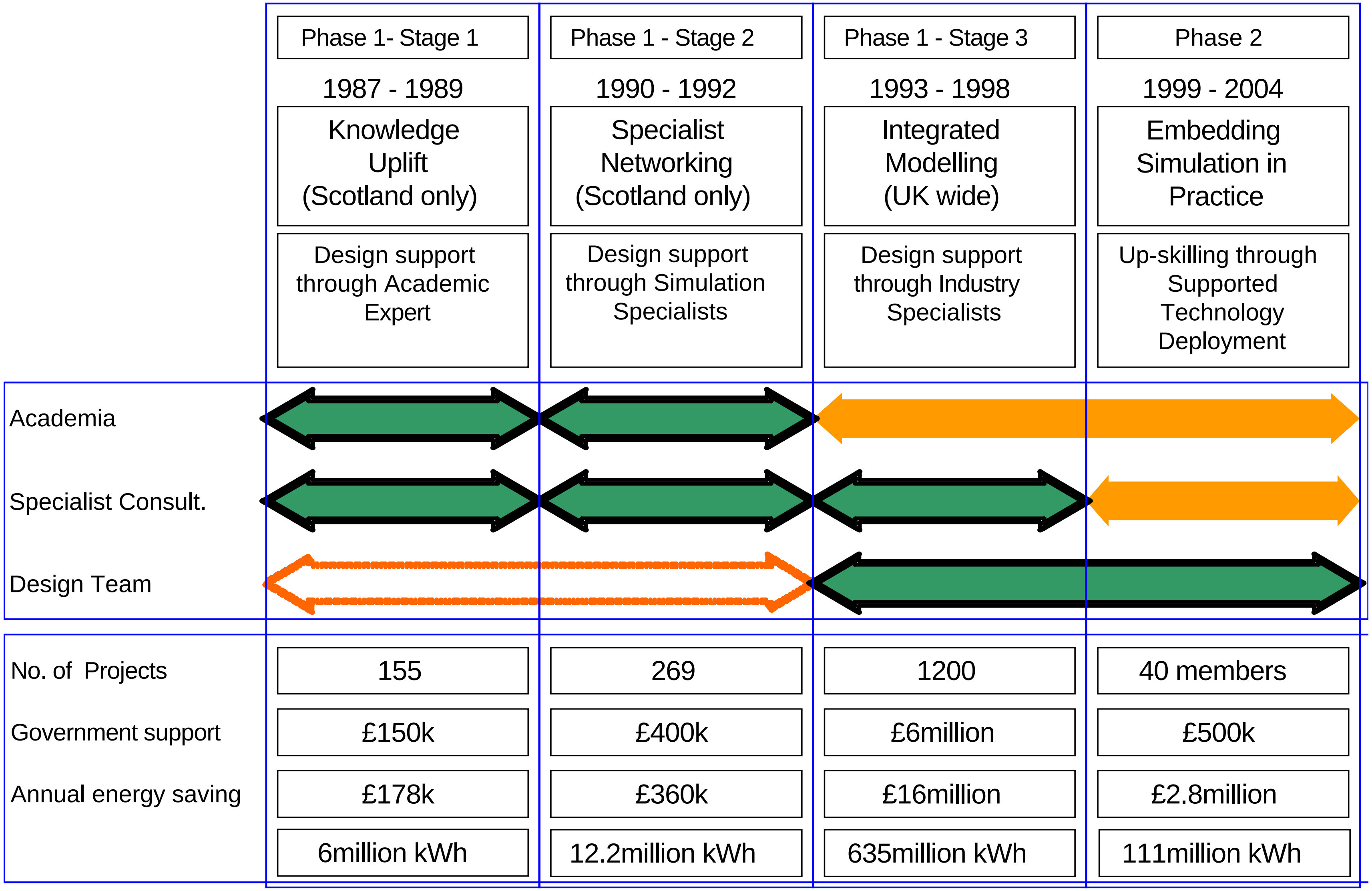
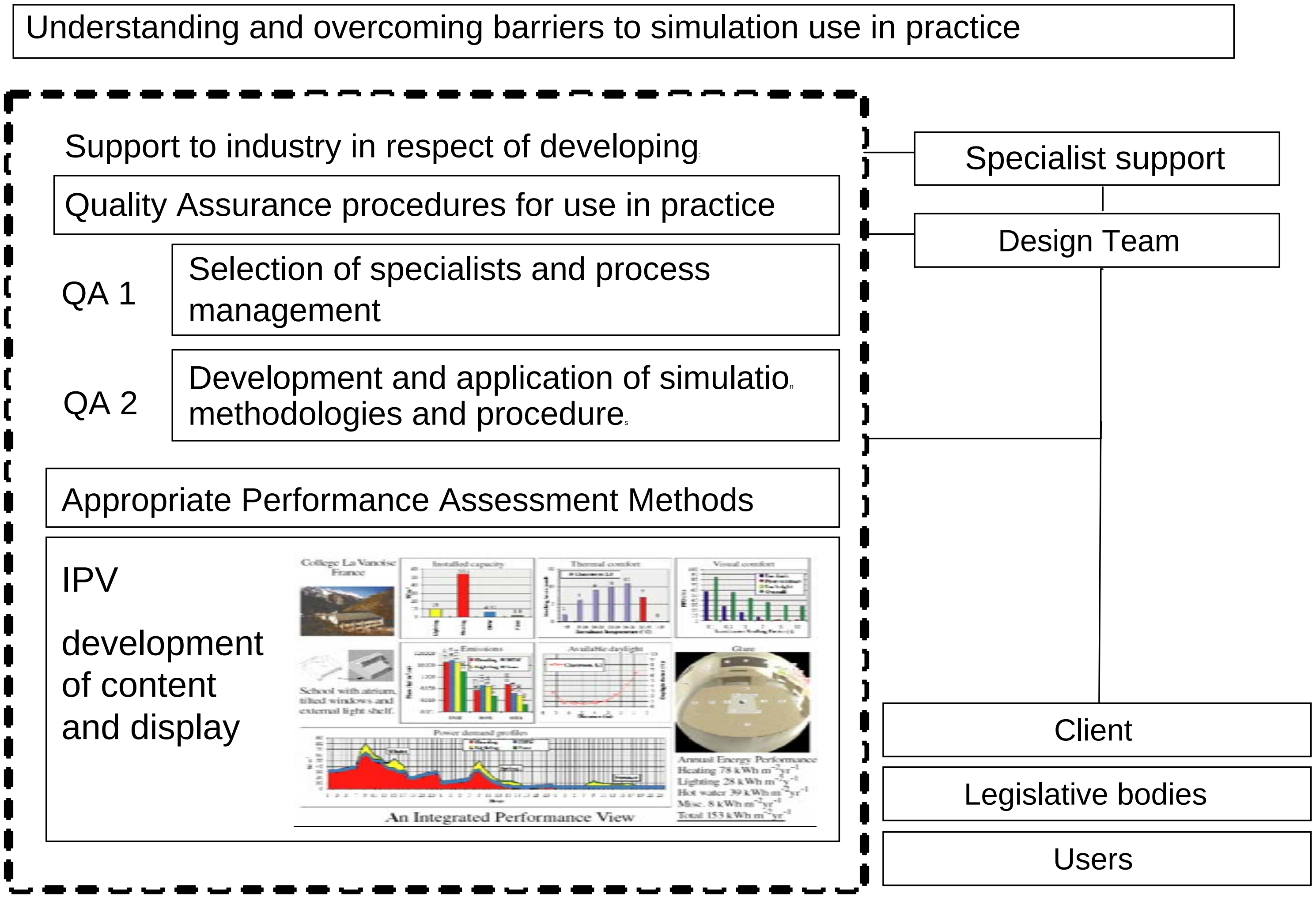


Figure B – Contributions of the work



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ABSTRACT

This thesis relates to a number of connected initiatives, which over a 20 plus year period assisted design professionals to transfer building energy and environmental simulation technologies from the domain of specialists to routine use in practice. It is written in the context of worldwide concerns relating to climate change, energy profligacy and depleting reserves of finite resources, from fossil fuels to materials, and associated legislative measures relating to the environmental impact of the construction industry.

The research conjectured and tested mechanisms, including performance assessment methods, quality assurance procedures and knowledge transfer, in order to encourage and support the uptake of simulation in design practice and to progress the embedding of the technology as a routine design process activity in Scottish energy sector and construction businesses.

By assisting the uptake of simulation within the professions, the reported work has allowed construction sector businesses to transform existing work practices and in the process to make a significant, measurable contribution to Carbon reduction targets over the last 20 years. Moreover, the work illustrates how the creation of support networks and an integrated, partnership approach between academia and practice can break down barriers to use in practices and increase the effectiveness of the transfer of new technologies resulting in cumulative positive environmental impacts that go significantly beyond the benefits of individual interventions. This conclusion is borne out by independent monitoring of the reported activities.

Chapter 1 - Energy Issues and the Built Environment

In the face of overwhelming evidence that human activity is adversely influencing the ecological balance of the earth, and that the associated fact that the built environment and transport account for more than half of the World's energy consumption, and solid/ gaseous waste, it is incumbent on those designing our shared future environments to do so with great care (Brundtland 1987).

Sustainable development is underpinned by a desire to ensure that our current actions do not adversely affect the quality of life of future generations. And according to the Brundtland definition, this means that society should "*meet our needs without compromising the ability of future generations to meet their own needs*." In practical terms this means that in achieving our goals, society should use no more resources than necessary, while at the same time leaving those who come later with the skills and knowledge to meet their requirements. But with advances in technology, the impact of meeting these needs is constantly changing and this has to be taken into account when making predictions and decisions related to an uncertain future. For example, there is a need for conservation of fossil fuel-based energy resources, but this will only become a critical issue if alternatives do not emerge within the necessary timescale - whatever that may be.

It is well recognised that in order to address the environmental, social and economic goals of sustainable development, efficient energy utilisation and the mitigation of environmental impact are important factors. And because the built environment consumes a large proportion of delivered energy and is responsible for most of the avoidable carbon-based emissions, many key government initiatives over the last 20 years have focused on this sector (Carbon Trust 2008) – the most significant of these are listed in *Table 1.1*. However, building energy systems are complex, and in the absence of a means by which the performance benefit of proposed measures can be predicted, such initiatives will fail.

Studies by ETSU (1997) in the late 1980s indicated that energy consumption in buildings could be reduced by 30% with low and no-cost interventions that have negligible impact on users in terms of the way in which they perceive and use buildings. However, achieving the UK and Scottish Governments targets of a reduction of 80% from 1990 levels by 2050, (UK 2008, SG 2008), will require a radical approach to new designs and refurbishments in buildings. In order to improve the likelihood that governments achieve internationally agreed emission reduction targets related to the built environment by the required date (EU 2003), a raft of new building regulations and associated legislation has been introduced. Building designers have a key role to play in delivery, and while the systems required to deliver such targets exist in large measure, the problem is the lack of a universally available decision support mechanism.

The issue of sustainability is controversial, and whether or not we believe that humans are the main cause of climate change, our profligacy in the use of finite resources, from building materials to fossil fuels, necessitates behavioural change. And if the climate continues to change at or near the predicted rate this will have significant implications for buildings, so there are other sound reasons for trying to be more sustainable. If nothing else, all of this will lead to further associated legislation with which designers will be compelled to comply. This thesis explores the issues involved in adopting a process based approach to the design of the built environment; relying on co-operation and partnership to better equip practitioners to cope with the challenges ahead.

Table 1.1 – Initiatives focused on energy efficiency.

Kyoto Agreement (1997)	Heads of Government commitment to reduce key greenhouse gas emissions in developed countries by at least 5% by 2008-2012 (relative to 1990; EU target set at 8%). This would result in 2010 emission levels that are ~29% below what would have been in the absence of the protocol.
Local Agenda 21	Commitment to reduce CO_2 emissions at the local level.
UK Home Energy Conservation Act (1995)	Local authorities responsible for preparing practical energy conservation plans to achieve a 30% reduction over 10-year period.
UK SAP Ratings Initiative	Introduction to the Building Regulations of a Standard Assessment Procedure (SAP) for domestic buildings.
UK Clean Technologies Programme	Promotion of waste minimisation, sustainable cities and new technologies (e.g. fuel cells, photovoltaics, efficiency measures).
Electricity market deregulation	Open market puts pressure on all sectors to change current practices, especially in relation to complementary demand- and supply-side partnerships.
Energy Action Planning	Requires elaboration of a range of appropriate sustainability indicators.

1.1 The need for a paradigm shift

Sustainable development is at the heart of economies Worldwide; despite this, and the fact that the majority of public buildings are being delivered against design briefs that call for sustainability, the number of sustainable developments actually being delivered remains relatively low. There are many reasons for this, and, while individual policies and legislative mechanisms deal with key planning, building form, materials and services issues, there are no universally accepted guidelines to assist those designing sustainable developments with the inter-relationships between these and the impact of building occupants and users of the wider surrounding environments. Those guidelines that do exist (e.g. Llewellyn & Edwards 1998) are rudimentary and tend to rely on mono-variate approaches when they increasingly need to take account of multi–variate interactions. These issues present significant barriers in terms of progress towards a more inclusive approach to design of the built environment.

In the past, when energy prices were low and the impacts of environmental emissions were less well understood, the range of energy consumption profiles in buildings was less of a concern both environmentally and politically. In the UK the RIBA Plan of Work (Appendix 1) (RIBA 2007) as applied by architects provided a methodology that was suitable for other members of the design team (structural, civil and building services engineers and quantity surveyors). This plan does not facilitate the inclusion of the increasing responsibilities of construction professionals which, post Latham and Egan (Latham 1994, Egan 1998), now range from sustainability and value engineering to changes to construction procurement procedures and a recognition of the benefit of better community engagement in order that the value of the embedded knowledge of building users can positively inform the process and delivered outcomes.

Traditionally, architects acted as the design leaders – producing, as a minimum, sketch designs to which the rest of the team would respond, in terms of calculating costs, engineering details, etc. Designs evolved through an iterative process and, in the past, this led to 'best-fit' engineered solutions rather than fully integrated developments. At this time, steady-state calculations as employed by building services and environmental engineers were deemed adequate when designing for worst-case scenarios where buildings were either sealed or had systems that operated regardless of interference from occupants. This approach has neither been adapted to incorporate wider sustainability concerns within the design process, nor does it facilitate the highlighting of key issues to the appropriate design team member at a pertinent time.

Furthermore, in the recent past, as engineering rather than passive solutions became the norm, buildings and associated systems could (to an extent) be developed without in-depth dialogue between design team members (not to mention the ultimate users of the building); solutions were increasingly designed to operate with minimal human intervention. However, as the need for energy conservation became apparent, and the impact on indoor air quality and occupant well-being became better understood, designs have migrated from 'sealed boxes' to solutions that make best use of natural cooling from fresh air, exploit thermal capacity, and capture solar and incidental gains where possible.

The result is that designers now recognise that steady-state calculations are no longer adequate given the dynamic and complex behaviours being addressed. Accordingly, Building Regulations in Scotland and the rest of the UK began to change from steady-state calculations to CO_2 target based solutions that permitted designers to demonstrate compliance through computer-based calculation tools that were then compared with traditional methods, (SBSA1998). In addition, new issues began to emerge such as the need to address climate change mitigation and the issue of future-proofing buildings against climate change.

The issue of method of recording energy savings was a recurring theme for the research reported here. Without full knowledge of primary fuel mix, it is difficult to draw conclusions as to environmental benefits of energy reduction/conservation methods applied. This was source of frustration over the period of the work, as government targets changed from kWh, to monetary value of savings made to CO_2 to Carbon. The approach adopted was to record wherever possible, a breakdown of fuel mix, associated kWh savings and the monetary value of these savings based on energy costs at the time.

Thus, as the issues of climate change and sustainable development have assumed a central role in shaping our built environments, the need for meaningful dialogue between all parties has become all the more palpable. Whether or not climate change remains the central driver for sustainable development, there is an over-riding need for conservation on the grounds of depleting reserves and resultant economic and social factors. Hence the need for a new design and construction approach that makes best use of the available skills of the design team, and all others involved, in order to deliver design solutions that reflect an understanding of and ability to positively influence the whole rather than the part (Nicol 2001).

In support of all of this, in September 2002 the industry report Accelerating Change (Egan 2002), was launched. This set an improvement agenda for everyone involved with the construction industry and, importantly, was compiled by representatives from across industry, government and the unions. It established a vision for the industry:

> "*…..for the UK Construction Industry to realise maximum value for all clients, end users and stakeholders and exceed their expectations through the consistent delivery of world class products.*"

In order to achieve national and international Carbon reduction targets, design professionals will be required to transform their existing design practices. This view is backed by recent post-Egan (NEC 2004) developments in terms of partnering in the construction industry for efficient delivery. In order to achieve this it is necessary to identify and alleviate the design practice barriers that currently impede those designers who wish to pursue a green philosophy.

1.2 Overcoming barriers to integrated working

For 30 years there has been talk of integrated design team working but little evidence of buildings that exemplify this process has emerged at the time of writing. In order to bring the professions together, each discipline needs to be aware of the unilateral effects of any design decision on the performance of the building as a whole, and not just the aesthetics, the cost or the thermal behaviour for example. Bioclimatic issues and a more holistic approach to sustainability mean that buildings can no longer be seen in isolation whereby the myriad building components, interactions with users and overall performance are intrinsically linked both internally and with the external surroundings.

In order to accommodate such thinking, there needs to be a recognition of the fact that an overhaul of work practices is required and that significant improvements in design team interaction are necessary in order to equip the professions with better insights and the right tools for the job. Attempts have been made to tackle this at a number of levels in the past; research, educational and professional, and although in-roads have been made, some design practice and process-based barriers are more difficult to tackle than others. However, fortunately alleviation methods for some issues exist already.

1.2.1 Under- and post-graduate education

At the under-graduate level, attempts have been made to incorporate the multi-disciplinary approach - for example, within the Building Design Engineering (BDE) course at the University of Strathclyde (BDE 2008). However, it is challenging to deliver under-graduate courses that meet the requirements of more than one professional body year on year and as a result of this the BDE course at Strathclyde – which for a number of years included architecture, construction management, environmental engineering and structural engineering elements, has recently been replaced by the more narrowly focused Architectural Engineering – without the environmental engineering component. Concurrently, there have been attempts to support the professions by up-skilling individuals through the development of post-graduate Masters courses that aimed to broaden specific aspects of under-graduate courses relating to the construction industry along the lines of the requirements of SARTOR (*Standards and Routes to Registration*), as published by the engineering Council in 1997 (EC 1997).

The Engineering Council had last revised its standards and routes to registration in 1990, and it had been recognised for some time that standards in engineering study programmes had been failing to meet the requirements of the industry in respect of meeting various Government targets. In the construction sector, the drive for engineers to meet specific needs rather than integrated meant the loss of broad-based skills, and engineers able to take an overview of the whole of design and construction. In response, SARTOR 97 aimed to address these deficiencies by on the one hand raising the general standard at all professional levels and on the other by broadening the perspective of all engineering courses, in order to meet new requirements and legislation. Overall, the aim was to produce better-informed professionals through the delivery of 'matching sections' (Fisher 2002) that were recognised by the appropriate professional bodies.

At a post-graduate level, within UK academic institutions as elsewhere there is an established track record in the development of simulation tools for practitioner use. At the University of Strathclyde, for example, much research has addressed the issue of strengthening links between academia and the industry – both with design practitioners and with commercial tool vendors. This has been a sensitive area in the past partly because building simulation is a relatively new activity and so new businesses are nervous of competition. Also there are added tensions in the construction industry due to tight profit margins and a culture of risk avoidance. As a result of this, designers have traditionally been nervous of the cost and the risk of integrating new activities into an already busy schedule – especially if they do not appreciate the nature of the added benefits.

1.2.2 Continuing professional development

Outside of the academic institutions, Continuing Professional Development (CPD) has a potentially pivotal role to play in up-skilling existing professionals. The importance of CPD *per se* is already recognised by the professions with many already requiring a minimum commitment of around 30–40 hours of accredited CPD to be undertaken by qualified professionals annually. However, in order for CPD to assist the progress of breaking down barriers to new work methods, there needs to be recognition from the professions that the old methods are no longer valid. Evidence of this is emerging at a regional level, with the various professions advertising CPD events across the disciplines to attract a wider audience and to foster inter-disciplinary understanding, and also through the introduction of less specific topics, e.g. in CIBSE, the introduction of CPD on wider sustainability issues once seen as affecting engineers through energy efficiency and renewable energy sources but now expanding to Carbon emissions, climate change and micro and macro aspects of sustainability.

The introduction of the Energy Performance of Buildings Directive is also driving the need for integrated assessment tools across the disciplines and many of the professional bodies are in the process of seeking accreditation for the implementation of this legislation.

1.2.3 Integrated performance analysis tools

In the context of the development of tools to support integrated working, building simulation tools have long been the preserve of a few specialist consultancies rather than being used where they can have the greatest impact - within construction design practices. This has resulted in additional costs for designers (time and financial) in terms of buying in specialist services. In addition, the designer is not able to fully explore the design potential: being restricted by what the specialist reports back.

There are well-documented reasons for this situation: most notably the perceived difficulty of using simulation tools; the associated cost (hardware, software licenses, staff training); and liability issues. Also, the construction industry is traditionally a poor investor in research and development, preferring to operate core business activities on proven ground.

In order for design practice to gain maximum benefit from the potential of simulation, simulation must be embedded within the design process. The reasons for this are well documented by Selkowitz *et al,* (1992). Most problematic issues are that members of the design team will require access to models at different stages as the design progresses and that the issues surrounding the exporting and retrieval of models by multiple users are entirely non-trivial.

This is further complicated by the fact that over the last two decades the construction industry, in attempting to become more streamlined, has moved increasingly away from the notion of integrated working towards a risk averse, defensive culture – despite the best of intentions. Instead of traditional design teams with architect and client overseeing the process, we are now faced with: value engineering, nominated subcontractors, diminishing direct labour resources and skills shortages, thus the delivery mechanism is now one step away from design team control. All of this makes it more difficult to know exactly what is going to be delivered at the end of the day – so, is there any real point in undertaking simulations to predict performance when for many all that matters is ‘on time, on budget’?

The problem in terms of taking the next steps may have at one time related to lack of information, but this is no longer the case. In fact there is no shortage of sustainability information and a plethora of design guidelines exist for both designers and clients (from bodies such as BRECSU, BRE, CIRIA, BSRIA, E&F Spon etc.), rather, the problem is a lack of a procedure for integration of the emerging sustainability issues into the design process. And in the absence of a framework within which to work, those designers who wish to pursue a green philosophy face significant barriers within a process that tends to be piecemeal, and ridden with gaps. In order to tackle the problems, and to make the required degree of progress, a paradigm shift is required, involving a complete change of mind-set in terms of the design process.

1.3 The need for a support environment

Through recognition of the potential of integrated performance assessment to address such questions, interest in adopting a simulation approach began to make the transition from the domain of the academic specialist to the domain of the practitioner. This has not been a straightforward journey. Just as there are barriers to attaining emissions reduction targets, there are barriers to the application of the very tools that may be employed to explore approaches to emissions reduction.

This thesis reports observational and practical research into the development of mechanisms to support the routine use of building simulation in design practice. It describes the achievements resulting from a variety of devices, from general awareness-raising to in-house support on live projects. At all stages the aim was to bring the design team together by using integrated design techniques to develop innovative solutions, rooted in sound environmental performance and best value. The model adopted has allowed businesses to progress at their own rate, and to build skills and confidence to suit their particular needs.

The thesis documents the extent to which the different trialled mechanisms helped designers to overcome the (then) obstacles to simulation use in practice. It also reports how the development of quality assurance procedures and simulation methodologies helped to build confidence in new tool users. The work to date has prepared practices to respond to the implementation of new and impending legislation in the UK and the rest of Europe (EU 2003, Sullivan 2007). The core contention is that a partnership approach is best enabled by the deployment of integrated simulation and that this is key to the successful delivery of sustainability objectives.

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Chapter 2 - The Capabilities of Integrated Simulation

Despite the fact that governments by now accepted the fact that profligate use of fossil fuels was having a negative impact on the environment, and that the need to conserve energy was a priority to address Carbon emission reduction targets, there was no consensus on how to monitor the impact of measures to address these issues. For the construction industry for example, traditional design methods lacked the level of detail required to predict the impact of climate change on the energy and environmental performance of buildings, hence the need for a new approach.

Although dynamic simulation tools had existed since the 1970s, and despite their ability to accurately simulate buildings and their systems, their use had been restricted to specialist modellers who apply the tools on users' behalf. The principle reason for this was that in order to use such tools in earnest, users require in-depth knowledge of a range of thermodynamic processes, environmental systems and controls issues.

2.1 Design tools

Integrated simulation offers building designers a spectrum of new analysis possibilities. Prior to the advent of simulation, computer-based design tools traditionally relied on simplifying reality in order that calculations could be undertaken manually. Dynamic, integrated simulation on the other hand uses complex mathematical models to represent energy flow paths and their interactions as they vary over time, thus allowing an in-depth analysis of the factors that influence the energy and environmental performance of buildings. This provides users with:

– the ability to handle a level of complexity hitherto not possible;
– the ability to address all relevant environmental issues; and
– the ability to explore all energy flow paths simultaneously.

By employing detailed building input data and using realistic weather data, dynamic simulation allows designers to understand the relationships between thermodynamic interchanges as they actually occur in buildings. This allows designers to explore the complex relationships between form, fabric and systems (conventional and renewable) in terms of the underlying dynamic transfers of heat, mass and momentum. In this way simulation allows the exploration of design issues in a holistic manner and in a way that respects the integrity of the actual physical system.

Figures 2.1 and 2.2 illustrate graphically the difference between simplified and detailed models. Figure 2.1 focuses on a subset of thermophysical processes, taking account of individual energy exchanges at a single point in time, but not the interactions of these exchanges and excluding some processes altogether. In order to understand the difference between the simplified, steady state method and a simulation approach: simulation treats all construction materials, room furnishings, occupants, energy systems, equipment and so on, as separate and variable nodes within the system being analysed. These nodes are dynamic and thus interact in competition with all other nodes in the space under consideration. Thus, the interactions not only vary over time, they are also interdependent. Figure 2.2 illustrates these time variant flow exchanges, with each energy flow or behaviour having a knock-on effect on other exchanges taking place at the same moment in time in the space being analysed.

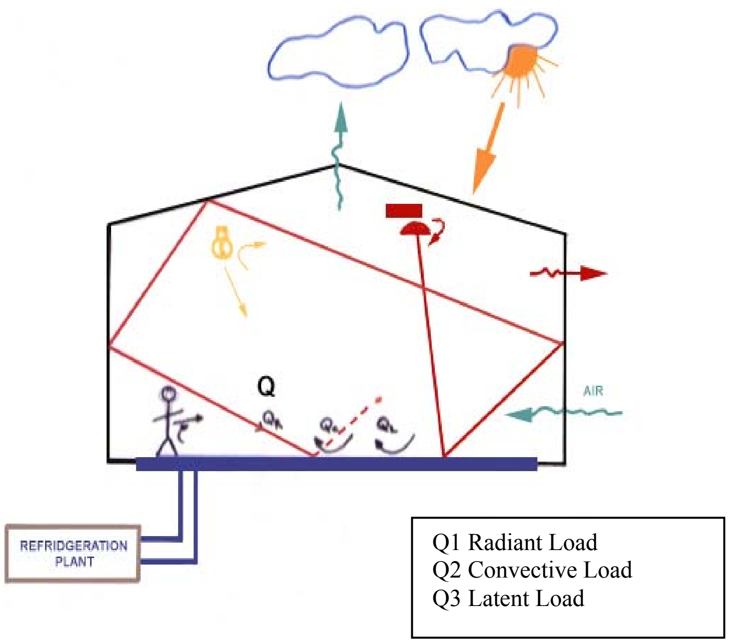

Figure 2.1 A simplified energy model

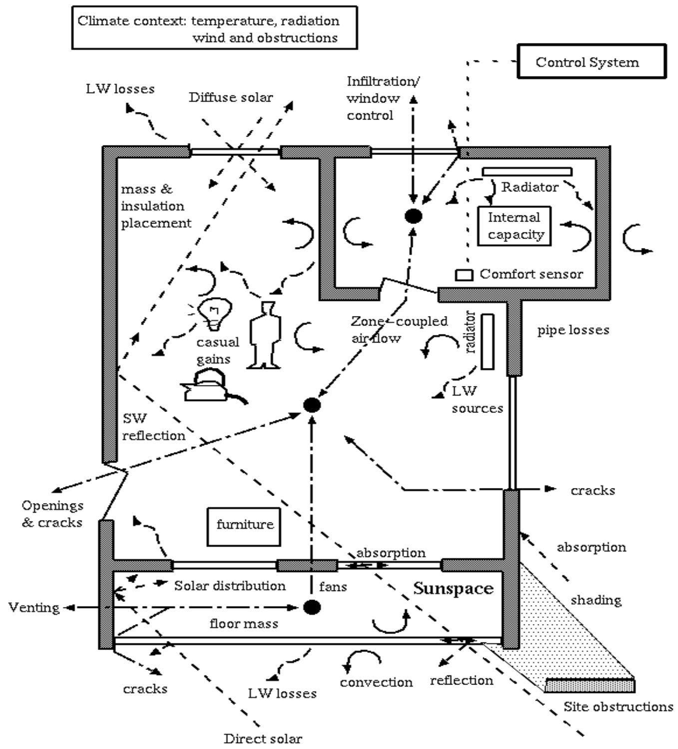

Figure 2.2 A detailed energy model

2.2 Barriers to routine use of simulation within the design process

At commencement of this work, in 1987, many designers were already aware of building performance analysis systems, however, they were not as yet in a position to differentiate between steady state calculation tools and dynamic simulation. Few were in the habit of routinely using computers in day-to-day design work, let alone deploying energy analysis software of any type. Thus, it can be conjectured that several barriers existed in relation to the routine deployment of simulation within the design process. Over the years these barriers have been documented by various users and researchers: ranging from the need for specialist computing equipment, through a steep learning curve, to fear of unrecognised data input errors and lack of credibility of predictions Howrie (1995). There also remains a perception that simulation is costly and slow, that users lack trust in outputs and in their ability to interpret results, and progress is also hampered by a lack of recognised quality assurance procedures, poor interoperability between tools and an ongoing problem in relation to the jargon associated with the technology (Hand 1999, Donn 1997).

All of the above can be traced back to one or more of the following seven issues, which continue to present barriers to routine tool use in practice:

- hardware and associated staff resources;
- user interfaces;
- problem definition;
- performance assessment;
- results analysis;
- quality assurance; and

– business integration.

The issues were not all equally weighted, and although solutions were required in all cases, some aspects could be addressed more easily than others. The theme of barriers to tool use is explored in the following sections and the issue of barrier alleviation is explored at length in chapters 3 and 4 in the context of moves to embed simulation as a mainstream design process activity.

2.2.1 Hardware and associated staff resources

Unlike simplified methods, simulation tools require extensive computing power in order to undertake the required number crunching. This meant that those undertaking simulation in the 1980s and 1990s needed access to specialist computing equipment with a level of power that was only available from workstations. Only this computing environment had the power to contend with the simulation demands and offer the type of graphic interface required to communicate complex results. At the time, such workstations were beyond the reach of most practices due to the high associated costs and the unfamiliar operating systems such as Unix. In addition the specialist staff required to operate such equipment were not routinely embedded within design practice at this point in time. This scenario began to change in the early 1990s as personal computers emerged and rapid software evolutions started to take place. As a result, this barrier began to recede (Lam & Mahdavi 1991), but initially the costs remained high, and although large design practices began to acquire desktop computers, for the majority this was not yet feasible.

2.2.2 User interfaces

Prior to the development of integrated simulation, analysis of energy and environmental performance relied on simplified calculations that set out only to determine loads in support of the sizing of heating/cooling plant. The new simulation programs allowed users to explore in detail the multi-variate performance (temperature, energy, comfort, environmental impact, etc.) that arises when occupants interact with buildings as they respond, in turn, to weather and control system influences.

Compared with simplified tools, which derive from many in-built assumptions, simulation requires users to input large amounts of data, much of which is unfamiliar and expressed in an unfamiliar language: terms such as 'atmospheric turbidity' and 'thermal diffusivity' are not atypical within a simulation program, while materials may require more than one defining parameter (conductivity, density, specific heat capacity, moisture content, emissivity, absorptivity, etc.). All of this results in a steep learning curve for new users and can create confusion and a lack of trust in the programs, causing novice users to doubt themselves and so reverting to simplified alternatives due to a perception that simulation tools are difficult to use in routine design work.

As the power of integrated simulation has increased, the need to develop interfaces that support a structured approach to design hypothesis specification and evolution has emerged as a non-trivial issue. Increasing the user-friendliness of a program is often done in a manner that belies the true complexity of the issues to be analysed, there thus a balance to be struck between protecting the user from the vagaries of the program and allowing access to the complete functionality of a powerful, multi-domain simulation environment. The problem is compounded by the fact that users' needs continue to evolve with experience, suggesting a need for an evolving interface – i.e. one that would support the transition from novice to experienced user, providing early stage support and offering insights as to more novel approaches as the users' understanding evolved. How this would be effected in practice remains an issue at the time of writing in 2009.

At the outset of the presented work, there existed a perception that as soon as users had access to better interfaces, all of the barriers to the use of integrated simulation in practice would evaporate. The reality is often the opposite with the user-interface giving rise to as many problems as it solves. On the one hand, particularly at the time of the commencement of the research, despite claims that elegant interfaces empower users, the fact remained that to follow the general developments in user-interfaces was not necessarily to the betterment of simulation, a) because this can lead to more effort going into the interface than the programs it supports, b) because highly developed interfaces 'eat up' computing power (Beranek and Lawrie 1989), and c) because excessive functionality can cause confusion and clutters the objectives (Bailey 1989). There is no easy answer to this dilemma and attempts to develop user interfaces over the years have been fraught with problems despite the substantial increase in the available computer power. The (then) lack of support for program use in practice and the absence of quality assurance procedures relating to model evolution and performance appraisal procedures were seen by designers as major barriers to the routine use of simulation modelling in practice. The issue of user-friendliness of interfaces is a recurring theme, and is discussed further in chapters 4 (4.4 and 4.5) and 5 (5.2).

2.2.3 Problem definition

In the early days of simulation, the methods available for developing building models bore no resemblance to the CAD-based systems available today. Visualisation of building designs beyond drawings and artists' impressions was still a pipedream for designers in practice. Indeed, building geometry specification was typically undertaken by the laborious inputting of co-ordinates, and in the earliest simulation tools, visualisation was not supported in any format.

Because simulation specialists are not building designers, and building designers were not (yet) proficient modellers, the mapping of design questions to simulation intent was a particularly challenging activity. In addition to the barrier imposed by an inability to visualise the problem to be modelled, the profession had no real understanding of how best to abstract a building as a physical entity into a model suitable for simulation (Tufte 1983). Furthermore, an appreciation of the level of detail required to answer the design questions to be addressed was a skill that had yet to be acquired. This gave rise to an additional barrier imposed by the fear of user error in inputting data and an associated concern of a potential discontinuity between program capabilities and the scale and complexity of real buildings (Barakat 1987). These issues are addressed in detail in chapter 3, section 3.5.

The creation of appropriate models that are suited to exploring the key issues is an art. It is equally as possible to create an overly complex model, as it is to over-simplify the model to the detriment of addressing the critical aspects of the design. Thus, the use of simulation was at the time seen as costly and slow, with no guarantee of useful results.

2.2.4 Performance assessment

Underlying model construction is the question of appropriateness: the model may be accurately constructed but is it the right model to answer the questions? What analysis does the profession need to undertake and at what level of detail? Is one model enough to explore all pertinent aspects? Can the same model be used to explore contaminant dispersal, lighting distribution, summertime overheating risk and annual energy consumption? If not, what level of detail is required in each separate model?

The time required to extract and understand simulation outputs and results in terms of design performance predictions should not be underestimated. Insufficient time invested in analysis can contribute to misinterpretation of results and a failure to spot significant issues.

Although simulation software provides detailed information on the problem analysed, often this does not directly answer the design questions being posed. For example, how can an office be naturally ventilated? To answer this, the designer will have to define adjustable leakage paths and then conduct simulations against representative wind conditions and occupant interactions. While this approach will quantify the time varying air change rate, it will not directly answer the question as stated. These issues are discussed in chapter 3 section 3.5 and chapter 4 section 4.4.

Such issues identify a need for standard performance assessment methods corresponding at least to the design issues routinely addressed in practice (Hand 1991). The work reported here did not involve the creation of such a method, but assisted tool developers and researchers working in this area with the development of methods that met the needs of the industry, based on observations of supported simulation use in practice.

2.2.5 Results analysis

Even when a user is confident with a program's inputs, can the user trust the outputs? And if so, results interpretation can present significant problems. In the absence in fully integrated models, how can a designer transform simulation predictions into design action? How can a designer be sure which design parameter is driving the results? Ultimately, the only way to assess the accuracy of a simulation program is to construct the building, monitor its performance and compare the actual and predicted data. While tool developers may have reason to be confident in program outputs, there existed at the outset of the research no mechanism whereby this confidence could be passed to users. The main reasons for this are twofold:

– the multi-variate nature of the problem makes it difficult to identify the design parameters that give rise to performance outputs; and
– each design has unique characteristics that make it difficult to compare outputs across designs or with benchmarks.

This identifies a need for an integrated assessment method that allows the user to view a variety of design issues simultaneously, backed up by a fully integrated design environment and tool interoperability. However, at project commencement the professions were neither equipped to build even the simplest models nor to interpret and translate the simulation outputs into useful design action. See chapter 3 section 3.5.

2.2.6 Quality assurance

Simulation gives rise to new complexities and an explosion in terms of the number of issues to be considered. At the commencement of the study, consultants were wary of simulation because of the lack of agreed application procedures: Kaplan (1992) suggested that, "*models are to error as sponges are to water*". Users were easily frustrated by systems that did not support model creation, documentation, archiving and retrieval systems, designed to trap errors. This was another non-trivial issue; Parand and Bloomfield (1991), and Chapman (1991) warned of the complexity of this task. While the key issues to be considered in setting up a quality assurance procedure had previously been identified (by BRE and CIBSE), these remained unresolved at the commencement of the work:

1. project initiation;
2. identification of objectives;
3. mapping of objectives to simulation tasks;
4. identification of uncertainty & risks;
5. development of procedures and maintaining an audit trail;
6. translating simulation outcomes to design evolution;
7. client reporting;
8. model archiving and sign-off procedure.

2.2.7 Business integration

A study was undertaken by System Simulation Ltd and Industrial Market Research Ltd for the Scottish Development Agency in 1980 (SDA 1980), in the wake of the energy crisis of the 1970s, which saw a 550% increase in energy costs from 1970–1979. The conclusion, based on market research and interviews with architects, design engineers and building clients, was that the time was right for the setting up of a UK-wide energy advice service addressing energy efficiency in the built environment. The report emphasised the need for service delivery through an academic specialist base, due to the perception that the industry did not possess the necessary in-house skills to offer such advice to building clients and non-expert designers.

Furthermore, the study revealed that designers were intrigued by the prospect of using design tools within the design process, in particular to answer the questions posed by an emerging interest in passive solar, low energy and green design. It also revealed that the expectation was that design tools should be easy to use – implying simplified tools such as BREDEM (Anderson 1985) and the LT Method (Baker 2001) – and that the simulation tools required to answer complex questions should be employed by specialists on behalf of design teams. Design-process integration was not yet seen as an option for in-house use because the issues to be tackled were seen as insurmountable in the short term.

It was recognised then (as now) that adopting a computational approach to design could make a valuable contribution to the mitigation of climate change impacts and the wider goals of sustainable development (Amor *et al* 1990). In order for this to happen, the tools needed to be fully assimilated into the design process. Such integration would require a paradigm shift in the way designers do business, in short a complete change of mindset. From clients to designers, and project managers to contractors to manufacturers, those responsible for the design and delivery of buildings face many pressures and are often reluctant to tackle the barriers associated with adopting new methods into an already complex process; in spite of the fact that new and impending legislation now requires that these issues be addressed. In addition, the costs associated with staff training and maintaining up to date equipment and applications in a fast evolving technology area, places an additional burden on those practices that want to develop and maintain an in-house simulation capability, and so it is not always straightforward to adopt new methods, despite the apparent potential benefits.

2.3 Research method

At this point in time, the professions had already acknowledged that traditional tools lacked the level of detail required to address the questions now being posed by design teams and that there was a need for better more flexible methods and new ways of working. There was general agreement that simulation might provide the solution, but barriers to deployment were hampering progress. A research methodology was developed in order to conjecture and test solutions to the adoption of simulation as a routine activity within the real world, dealing with the time pressures of the design process, and quantifying the outcomes in terms of measured energy and environmental benefits. The work was undertaken in two phases over sixteen years, from 1987 to 2004.

In the first phase of the work, the industry demand for and potential benefits of simulation to deliver energy savings and environmental improvements were explored through observational research. This was undertaken through the author's role as in-house technical researcher in the delivery of a simulation based design advisory service, which provided design practitioners throughout Scotland with risk free access to simulation experts who undertook simulations on behalf of designers, outside of the design process and in parallel with normal working practices. This work is broken down into three distinct stages: encouraging the uptake of simulation in design practice through knowledge uplift; development of a support infrastructure using specialists to deliver the expertise required and development of a design support service for integrated modelling.

The second phase of the research, from 1999 – 2004, took the work a stage further by exploring the potential to create and embed an in-house energy and environmental simulation capability within energy sector businesses. This was undertaken through a series of measures based on a phased, supported deployment initiative, whereby design practices could begin to up-skill staff and adopt new technologies in a incremental, non-disruptive manner. The aim was to move simulation from the domain of specialists into the hands of the design team at the most appropriate point in the process to influence sustainability related decision-making. The research method entailed working directly with practitioners to identify and analyse barriers to the routine use of simulation tools in practice. The underlying hypothesis is that simulation can provide answers to design problems quicker, cheaper and better than conventional tools, provided the appropriate mechanisms exist to support users. This shift in terms of controlling the decision-making process is illustrated by figures 2.3 and 2.4 (Clarke *et al* 1995).

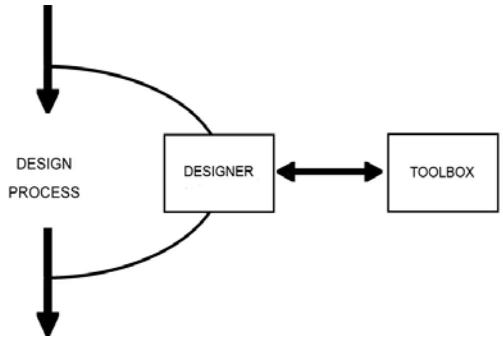

Figure 2.3 – Phase 1 - Facilitated (protected) access to tools.

Figure 2.3 Illustrates the approach adopted by the first phase of the work – whereby simulation was employed outside of the design process with a view to encouraging tool use, while allowing the design process to carry on unhindered.

Figure 2.4 Illustrates the subsequent approach employed whereby an attempt to create a 'pull' for the new technology by the industry, minimising risk to the design team by providing in-house support for simulation tools to be embedded within the existing design process.

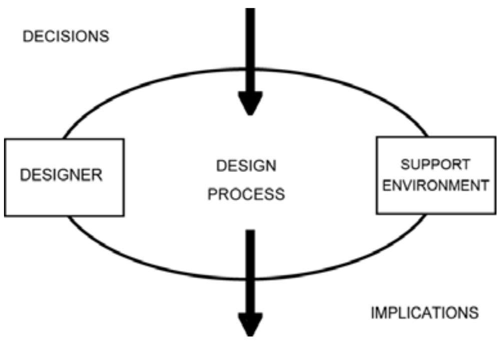

Figure 2.4 – Phase 2 Supported use of tools within the design process.

The work was undertaken in the context of two separate but complementary government funded initiatives over the period 1987 – 2004. Phase 1 (1987 – 1998) explored the industry's appetite for simulation through the Energy Design Advisory Service (EDAS 1998). Phase 2 (1999 – 2004) the Scottish Energy Systems Group (SESG) provided a vehicle to transfer the technology to practice. The thesis utilises data from these observational research activities to explore the impact of the adoption of building energy simulation on design practice. The work is reported chronologically based on the analysis of outputs from these initiatives over the period 1987 - 2004. Each stage of the work was informed by the outcomes of the preceding stage.

The scope of this thesis is not to review individual simulation programs, but to examine the barriers and opportunities to their use in design practice. For details on the capabilities of specific modelling tools, the reader is referred to the Building Energy Software Tools Directory Web page hosted by the US Department of Energy (DoE 2008).

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Chapter 3 – Assisting the Use of Simulation in Practice

3.1 Raising practitioner confidence

Around 30 – 35 years ago, researchers involved in the development of the dynamic simulation tool ESP-r (ESRU) at the University of Strathclyde's Architecture and Building Aids Computer Unit (ABACUS) and a few practitioners began to explore whether these tools might be of use within live building projects. There was a high element of risk attached to this, in that the consequences of acting on the outputs of such tools was at the time untested, and simulation was not yet well developed for this purpose. However, by working with experienced engineers, who could apply intuitive knowledge to the problems addressed, these pioneers were able to begin the movement of simulation from academia to the professions.

At this point in time, the focus was on the ESP-r simulation tool, and academic experts were responsible for undertaking the simulations, working closely with the design team. It was an era when designers and academics were sufficiently enthusiastic and curious about the possibilities to devote extra time to explore options together. Although simulation informed some of the decisions taken, typically, the same energy systems were installed as would have been the case without undertaking the studies. The simulation researchers and designers were learning together, and this required extensive discussion and interaction between the two sides. And while simulation was not fully tried, tested or trusted, it was always the new, novel, and big problems and challenges that it was expected to address.

However, a lack of trust in the results and the fact that practitioners were wary of the academics' approach to real world issues created tensions, but it was recognised that physical models could not provide the answers that were needed. And so the commercial world and the theoretical world tolerated one another in the absence of an alternative method to solve the increasing complexities thrown up by complex building forms and new materials and technologies ranging from innovative glazing systems, through breathing constructions to small scale renewables and passive design solutions. Lack of confidence in results was compounded by the absence of support for the application of tools in the real world, and a lack of monitored evidence that the new passive design strategies were appropriate to specific local climates.

Despite a number of initiatives designed to promote sustainable design as the accepted mainstream approach, and a plethora of information and case studies from respected organisations such as the Building Research Establishment, the Energy Efficiency Office and the Energy Technology Support Unit, support for application was often inaccessible or indigestible, in that reports were generally building specific and either extremely detailed or in summary case study format with no guidance on how to use the information within live projects. In addition, designers were often unaware of the existence of this information or how to access it. In the case of simulation-based appraisal, this remained the domain of specialists, and most mainstream designers were either unconvinced of its utility or intimidated by its complexity as an in-house tool.

As a result of existing associations between the University and leading-edge local engineering and architectural practices, researchers at Strathclyde and some engineers in the field had become increasingly involved in providing design support to the more innovative design teams that had recognised the need for new approaches to address emerging needs. These designers were aware of the emergence of simulation tools, and despite reservations, some took the risk of training staff to use these new tools – many of which had no elegant user interface.

In 1980, a report highlighting the potential benefits of a well marketed simulation-based energy advisory service was submitted to the Scottish Development Agency (SDA) by Industrial Market Research and System Simulation Limited (SDA 1980). The report identified that, for an outlay of £1.23 million, revenue of £1.47 million could be generated over 3 years. It also indicated that the industry was ready to respond to such an initiative, and that the (then) existing simulation capabilities were mature enough to deliver. Further, it recommended that the focus should be on the energy use of the existing building stock (BRE 1999, Carbon Trust 2008) and that advice on new buildings would form a less significant part of the market.

The 1980 report was not acted on at that time, but those involved continued to pursue its recommendations, and in 1986, the West of Scotland Energy Working Group facilitated the bringing together of ABACUS and the Royal Incorporation of Architects in Scotland (RIAS) to develop a project to explore the potential to encourage the uptake of simulation technologies within the construction industry. While the project gave rise to significant environmental benefits at the national scale, it also identified the potential to transfer the technology from the domain of specialists into the hands of practitioners. This project (The Energy Design Advisory Service (EDAS)), acted as a vehicle to undertake three stages of the research from 1987 – 1998. These three stages were not pre-determined, but were developed directly as a result of the outcomes of the previous stage. The sequencing of activity was as follows:

1. encouraging the uptake of simulation in design practice through the provision of design advice;
2. developing a specialist support infrastructure to advance this activity; and
3. linking of this activity with recognised research, design and development activity in order to assist government in meeting Carbon reduction and energy efficiency targets.

The associated research and development of these activities are discussed in the remainder of this chapter. The aim was to transform the construction industry in Scotland from one that had relied on the same tried and trusted methods since the 1930s to an industry that was ready to meet the 21st century trials of climate change and the decline of fossil fuels.

3.2 Encouraging use of simulation in design practice: Knowledge uplift

The first stage of the research began in 1987 and ran for two years. The objective was to address point one above, in other words to explore the appetite for the use of simulation in design practice by making available to Scottish architects and their clients a design support service, offering simulation-based advice on all aspects of energy efficient design in building, in the process, deploying a wide range of computer-based tools and drawing on the principles of energy conscious design. This was based on the hypothesis that; by providing a suitable support mechanism, building performance analysis tools could assist the industry to deliver more energy efficient and environmentally responsible buildings. The intention was to encourage uptake by providing building design professionals and their clients with protected access to simulation-based design support (Clarke & Maver 1991). Suitable building projects were selected by advertising the initiative and by offering two levels of support: the first level was undertaken at no cost to the customer, and generally related to simple studies that could be answered quickly, or that identified the need for a second, more detailed analysis. This approach generated a high level of interest and provided a large sample of projects for monitoring and evaluating effectiveness in terms of improving the energy and environmental performance of the Scottish building stock, achieved by making low energy design expertise more widely accessible.

Key decisions affecting energy consumption are made at the earliest design stages and, by collaborating with the RIAS, it was anticipated that it would be possible to influence architects as early in the process as possible thus maximising impact. While evidence was emerging that design engineers had already begun to recognise the potential benefits of simulation, it was felt that by engaging with architects, there was a potential to influence projects before many of the decisions affecting energy consumption had been made.

In order to encourage uptake, a light touch approach to information recording and analysis was employed to avoid overburdening users who might want to obtain answers quickly:

- practitioner and client details;

- a basic description of the design;
- the nature of the enquiry;
- the design stage of the project;
- whether the problem required an energy analysis;
- the cost of the supplied service;
- the recommendations made; and
- the potential energy/environmental benefits.

As the service was primarily aimed at architects, the recording system used the RIBA Plan of Work (Appendix 1, RIBA 2007) in order to record at what design stage the enquiry was made. A sample form is included as Appendix 2.

In some cases, the query could be answered by the supply of pre-existing information. More often, an initial, diagnostic consultation was required to analyse the problem and identify possible actions. If the potential for significant energy/ environmental improvements was identified, a recommendation was made to proceed to a detailed consultation stage, with up to half the cost paid by a government subsidy.

3.2.1 Monitoring stage 1

For the purposes of evaluation and in order to assess the potential uptake of the initiative, the project was monitored throughout and the outcomes and results independently verified (Eclipse 1989).

During the first stage of the research, the key objective of monitoring was to establish the demand for simulation within the design professions with a view to informing the ongoing development of the service, and also to gain an insight into the type of advice that users expected. This included analysis of market penetration, uptake of recommendations and value for money in terms of energy saving potential per £ spent on delivery.

Key questions explored in the monitoring exercise were:

- the actual requirements of users;
- how these requirements were met by the service in terms of translation of users' questions to quality of technical advice provided;
- impact on user attitudes and approach to the design process;
- comparison of users and non-users views of the potential to use simulation in the design process;
- energy saving potential as a result of the service;
- efficiency and effectiveness in providing advice;
- value for money; and
- future opportunities and the need for continued support.

The aim was to develop an understanding of users' perceptions of the capabilities of modelling and the questions that it could/could not address, what they would/would not be willing to pay for advice on, and to feedback to tool developers the impressions of the industry, not only to ensure that the needs of industry were being addressed by the research, but also to ensure that the industry was made aware of simulation benefits that it was not yet taking advantage of.

The following sources of information were used to gather the information required to investigate the above:

- recording and reporting documentation for individual studies;
- interviews with users and industry steering group members; and
- questionnaires sent to users and non-users of the service.

Monitoring was undertaken by circulation of a questionnaire to all users, with selective follow up through focus group interviews with a variety of user types. A similar questionnaire was also sent to all 2362 registered architects and the heads of 17 major building services engineering companies is Scotland. The response rate from users was high at 37%, whilst the response rate from the non-user group was low at 65 out of a total of 2379 (2.7%). In addition, 8 of 20 users who had paid for detailed simulation support were brought together in a focus group to establish how much of the advice provided had been of use and what proportion of the predicted energy savings were likely to be realised. Likewise some non-users were included in the focus group to establish what modelling methods they currently used and under what circumstances they would consider employing specialists to undertake simulation work on their behalf. An assessment of how much users were willing to pay for advice was also made. This activity provided a forum for users and non-users to express freely how they perceived the benefits or otherwise of simulation, and prompted a discussion on cost and value.

This revealed that there were two separate markets for simulation support, both of which this project was addressing:

– a need for a quick response on a variety of energy and performance related issues, by small and medium sized (mostly private sector) practices on mainly (but not exclusively) domestic scale projects – this was undertaken through the free, simple consultation; and
– a need for detailed energy consumption and building performance advice by energy specialists (mainly engineers and energy managers) on large and small scale domestic and non-domestic buildings – this was well covered by the (subsidised) detailed consultation.

Non-users of the initiative, were generally either sceptical, or had not yet identified the right project, but bringing them into the focus group provided them the opportunity to gain feedback from those who had benefited.

It was originally envisaged that free advice would require a maximum timescale of half a day. In practice, it was found that simple consultations often took between twice and ten times as long as anticipated due to:

– the administrative effort required to document and deliver the advice;
– the time involved in travelling to the enquirer's place of work;
– time required to deal with follow-up questions; and
– the time required to negotiate and establish the scope of a detailed consultation if required.

Thus, the efficiency of delivery of the service had been more difficult than anticipated due to a less rapid turn over and the fact that this meant the defining line between simple studies and detailed studies was less clear-cut. The matter of protracted timescales also highlighted that providing industry support with only one ‘expert’ delivering the advice, while maintaining impartiality, and addressing barriers related to lack of trust, could, unless well managed increase barriers related to delay and speed of response and therefore could adversely affect the ability to deliver simulation-based design advice in this way. The focus groups were, in the main, tolerant of time delays caused by this as they valued the independence of the advice offered, however, were the service expanded this could become problematic. Notwithstanding, investigation showed that identification of independent experts who would not be regarded as being in competition with those seeking advice, was a non-trivial task. Although a number of organisations and individuals who could alleviate pressure on the system were identified, only a few of these were employed to assist, due in part to a lack of familiarity with the organisations’ work, professional sensitivity (e.g. introducing a ‘rival’ professional to a client) and the fact that few organisations had adequate Professional Indemnity Insurance (PII) to provide simulation-based advice.

Number and type of enquiries

In the two years from May 1987 – May 1989, 155 enquiries were received, representing around 110 organisations using the scheme: 70% of these enquiries came from private companies (mainly architects), and 30% from the public sector. This provided an opportunity to gather meaningful statistics from a relatively large dataset. A questionnaire survey was sent to 100 users and a response rate of 37% was achieved. The responses identified the following key issues on which advice was required:

performance specifications and energy	24%
heating and ventilation	15%
insulation and interstitial condensation	14%
overheating problems, solar gain, comfort	11%
energy surveys, monitoring, targeting and management	9%
general demonstrations of what simulation could do	7%
climate sensitive design/renewable energy	7%
energy costs	3%
condensation issues	3%
other	3%

In other words, in the early days the primary concerns of users related to fuel saving and issues such as condensation and overheating. This indicated a tentative start in that the industry was willing to ask for support on issues that it was familiar with, in order that the outcomes could be benchmarked against what might be expected – a safe way of testing the initiative while minimising risk. As yet enquiries of an innovative nature were few, in part reflecting the lack of confidence, but also perhaps related to a lack of a benchmark from which to move forward.

The most common building types modelled at this time were education buildings and housing, representing high public sector interest, although commercial projects such as offices, sports facilities, industrial and retail buildings were also represented. For detailed studies, the most typical design questions related to building running costs, comfort, condensation, solar energy, control, energy surveys, audits and management. Around 25% focused on comfort and avoidance of defects rather than the energy efficiency issues originally anticipated. Although public sector users represented only 30% of enquirers, a higher proportion (around 60%) of detailed studies related to new and existing public sector housing, schools and offices, indicating the importance placed by the public sector on the future running costs and maintenance of its stock. This also highlighted the need to explore how to better engage with the private sector on the benefits of detailed analysis on larger projects as there appeared to be a greater reluctance to move forward in this sector. Further focus group analysis revealed that while the architects themselves were interested in the possibilities, their clients were not (yet) willing to pay for additional analysis, despite the fact that they would be the ones to benefit in the long run.

Over the two-year period, the work gave rise to an estimated annual energy saving of £178,000, equivalent to less than a one-year payback on investment. This figure was estimated from simulated predictions of energy savings, based on a heating fuel mix in Scotland at that time of 26% electricity (£8.50/ GJ) and 74% fossil fuels (averaged at £3.60/GJ) taken from the Scottish Abstract of Statistics 1989. The most commonly adopted recommendations related to energy efficiency and refurbishment improvements, with few clients being reported as willing to adopt fabric improvements beyond Building Standards requirements at this time, despite encouragement from their design teams. The inconsistency in an accepted approach the nomenclature used for measuring energy savings remained an issue throughout the project, however, future proofing of the data was maintained by recording fuel mix, energy use and cost.

In addition, capital cost savings of up to £21,000 were identified for the projects assessed. The market for simulation support was found to be well defined, comprising mainly of architects (who represented over half of the users) and engineers/energy managers (approximately one third of users). These users reported that they were unable to procure such services at that time from conventional building services engineering practices.

The surveys also revealed that enquiries typically related to projects with values ranging from under £100,000 to over £1 million. And when questioned about their willingness to pay for support, the focus group revealed that users would be unwilling to pay for advice on projects valued at less than £500,000. Access to simulation was reported to be of interest, but was regarded as an expensive luxury, not as yet readily available within the traditional design team. In research terms, this revealed that as most everyday project costs fall below this figure, it would not be possible to employ specialists in the long-term. There was a definite market for the technology, but to make a viable contribution, simulation would have to become embedded in practice.

In terms of how much they valued the support available, the survey questionnaire attempted to ascertain what the industry would be willing to pay for such a support service in the real world. Follow up focus group investigations revealed that users were willing to pay around £22 per hour for simulation advice, which, based on RIBA pay scales, related to an annual salary (then) of around £11,000; in other words, typical of a junior member of staff rather than an expert. The average cost of a detailed consultation between 1987 and 1989 was £2,500, although users indicated that they were willing to pay a maximum of £1,000 for advice, implying that they did not have any sense of the real cost or value of dynamic simulation. From a research viewpoint, this revealed two things, a) that users were not willing to pay the 'real cost' of including simulation within the design process at this point in time, and b) that while there was some evidence that they recognised the potential, they had no real understanding of the expertise required. The significance of this is explored further in the following sections on the next stages of the research. But at this point it could reasonably be concluded that the industry was not yet ready to bear the full cost of simulation as an externally provided service, let alone to consider the longer-term goal of simulation becoming an in-house design team activity.

The information requested at the outset of an enquiry, indicated that advice was most typically sought at one of three distinct stages of a project:

- 15% of enquiries were made at RIBA stage A or B (inception and feasibility);
- 61% at stage C or D (outline proposals/ scheme design); and
- 24% at stages E and F (detailed design).

This finding is significant in that, according to BS8207 (BSI 1985), the key stages at which energy saving potential can be maximised are stages A and B, indicating a high risk of lost opportunities with only 15% of projects applying this early in the design process. In addition, the surveys revealed that at this time, enquiries were largely problem driven, and so were made at later stages in the design process once the problem arose. Furthermore, monitoring identified little evidence of the early stage collaboration recommended by BS8207. The need to persuade designers to seek support at the earliest possible stage in the process was highlighted as a key challenge at this time and was taken onboard as an issue to be addressed through future focus groups.

An in-depth survey was undertaken on 8 of the 25 detailed consultations based on technical issues of interest and their replication potential. This involved not only questionnaires but also a follow-up focus group meeting with those commissioning the work. As with the simple consultations, simulation was generally undertaken at design stage A or B (inception and feasibility) and stage D (detailed design). In only one case was simulation used at the very early stages to probe strategic issues, and this was on a project where no building services engineer had yet been appointed. In all other cases, simulation was used to supplement the work of conventional building services engineers.

Furthermore, the respondents, from architects to energy managers reported that the available subsidy through this service offered access to simulation at a price they felt was cost effective. They also suggested that even if such services were available, e.g. from building services engineers, there was little or no incentive for the engineers to make recommendations that might include capital cost reductions, given that building services engineers' fees were traditionally based on the value of the equipment installed. At the time of writing this remains a contentious issue beyond a few innovative practices who charge for their services and not on the basis of plant costs. It was evident in the late 1980s that potential users of a simulation service in Scotland envisaged the service developed within this programme as a source of advice that was unique and not readily available from other agencies.

Focus group discussion also revealed that simulation had also acted as an adjudicator:

- to settle a dispute between design team members;
- to settle a dispute between a manufacturer and the client's representative;
- to compare various design options already identified by the design team; and
- to eliminate risks associated with energy issues early in order to prepare better briefs.

This outcome was unexpected, as although most users reported a view that energy conscious design should be provided by their design team/architect as a matter of course, they also accepted that in the short term, some were 'behind the times'. As a result, there was a consensus that users might be prepared to pay for such a service in the short term, especially if they felt that simulation could assist in sorting out differences in opinion and/or provide clarification on emerging design ideas, such as the use of thermal mass in passive buildings, or the significance of cold-bridging in well insulated constructions. Similarly, although most were positive about the service provided and felt they had received good advice, good value for money and useful recommendations, some felt that they were unable to use the advice directly, needing expert support (e.g. from an engineer or energy manager) to make full sense of the advice offered.

Significantly at this point in time, only one of the interviewees intended to set up their own simulation capability while in the short to medium term, 4 intended to continue to use simulation through the bureau service; 2 because of the high hardware costs associated with setting up such a capability. Thus, at this point in 1989, while a definite interest in the available technologies was identified, there was no evidence that the work undertaken thus far had managed to stimulate the transfer of simulation technologies to design practice.

3.2.2 Recommendations

The research revealed that in the absence of an alternative mechanism, a simulation support service, delivered through specialists could fill a definite gap in the market, allowing the exploration of alternative design options, and the potential of simulation to answer complex design questions. It was recommended that the initiative should continue to be funded to meet the emerging need; linking those seeking advice with simulation specialists who could provide the answers required. Key messages gathered anecdotally in delivering the support and through the monitoring results, in terms of the development of the service were the need for:

- greater concentration on convincing clients of the importance of energy issues;
- pooling and publishing information from this and other sources to support users;
- identification of additional specialists to support the initiative;
- use of additional detailed computer programs;
- preparation of standard forms for model data input; and
- improved information recording in terms of project details and advice given.

Taking the long-term view that in order to address future construction related environmental challenges, simulation would ultimately have to become an integral part of the design process, it was felt that addressing the above points would leave the industry well-placed to support research into the development of an initiative to teach users how to do this work themselves.

Monitoring also identified two key issues that the research initiative was already tackling successfully:

- the need of small-to-medium sized architectural practices for a speedy response on a wide range of energy and building performance issues – addressed through the free simple consultations; and
- the need of energy specialists such as energy managers for more detailed support on building performance and energy consumption issues – addressed through the subsidised detailed consultations.

To date, there had been little opportunity for early design stage involvement, when intervention could be most beneficial in terms of energy reduction and improved performance, therefore the research recommended that effort should be expended in raising awareness of the importance of seeking advice early, and in advertising just how beneficial this could be, through case study examples, newsletters and other media.

In order to ensure a level playing field, a formalised register of organisations possessing simulation and other modelling skills was established. The organisations included those capabilities in a wide variety of programs from simplified tools such as BREDEM and

Hevacomp, to detailed simulation tools such as Tas and ESP-r. This not only reduced the burden on the in-house researcher/specialist, thus providing greater opportunity to observe the outcomes, but would also begin the process of moving simulation out of the academic domain into the hands of the industry – albeit in a protected, hands-off manner in the first instance.

As a transparent system was required for matching consultants from this register with clients requiring support, there was a need to maintain the bureau service, to broker the matching of specialists with users and to provide advice and support with the implementation of simulation results. Legal issues associated with nominating external consultants without PII cover for providing simulation-based advice remained a concern.

Monitoring at this stage suggested that in terms of addressing the barriers outlined in Chapter 2, provided the speed of response could be maintained, the initiative had largely protected the industry from time related, trust/confidence, equipment related and quality assurance issues. Tat this point in time the cost barrier was addressed by the financial support available, but as monitoring had indicated that the industry was not (yet) ready to pay the market rate for such support, it was recommended that this issue should continue to be monitored closely in the second stage.

In order to fully establish the potential energy saving and environmental benefits of using simulation within the design process, a more formal and standardised recording system should be developed for use in the next stage, introducing the users and providers to the importance of quality assurance. Few enquiries at this stage related to interoperability of tools, due in part to the industry building up trust through projects that it well-understood, and in part to the fact that such enquiries were as yet rare.

3.2.3 Issues remaining

As reported in earlier in section 3.2 at the end of the two-year pilot, the 155 consultations resulted in an estimated annual energy saving of £178,000 (£106,000 for simple and £72,000 for detailed consultations), equivalent to just under a one-year payback on Government investment. In addition, capital cost savings of up to £21,000 were identified for a number of projects assessed. Two further points of note were that:

- the quoted savings were not cumulative and would continue well beyond the first year of implementation; and
- it was anticipated that users would be likely to implement similar measures on subsequent projects.

This indicated that there was potential for much greater energy and environmental benefits from the use of simulation within the design process, beyond the scope of the projects on which advice was provided. Notwithstanding, the potential benefits of the service in energy saving terms were estimated: It should be noted that despite recording energy saving potential at the end of a consultation, it was necessary to interview users regarding how much of the advice offered was actually implemented. Improved recording of the potential and actual benefits of the service was a key recommendation, as was the continuation of focus groups as a means to monitor the effectiveness of the initiative.

A caveat on the above is that the actual savings/environmental benefits may well have no direct relationship with the predicted benefits as no account can be taken of the expertise with which advice is incorporated into the design let alone build quality on site, building use or occupant behaviour (Porteous & Ho1997, Porteous & MacGregor 2005).

A key issue identified early in the work was the lack of support (from clients and government) for further analysis post-project completion, as clearly the true impact of advice delivered through simulation support can only be measured by post occupancy evaluation and energy and environmental monitoring. Other areas identified where simulation could be of untapped value were the use of simulation for diagnostics and for assisting commissioning. Although the latter are at the time of writing (2009) becoming more commonplace, the issue of the use of post occupancy evaluation remains contentious, in that while designers in the main, fully recognise and support this need, clients seldom do. Post occupancy studies are not only time consuming and labour intensive they also require a level of expertise, which makes them expensive to undertake, however, to provide the feedback that the construction industry needs, it is arguably necessary. The benefits are well documented in the PROBE[1] studies undertaken by the Usable Buildings Trust for CIBSE between 1995 and 2002 (USB 2008). The timescales of this project did not allow for this type of evaluation, but for the next stage it was recommended that better recording and monitoring procedures be put in place. It was perceived that this could facilitate a better understanding of

[1] PROBE (Post-Occupancy Review of Buildings and their Engineering) was a research project,which ran from 1995-2002 under the Partners in Innovation scheme (jointly funded by the UK Government and The Builder Group, publishers of Building Services Journal). It was carried out by Energy for Sustainable Development, William Bordass Associates, Building Use Studies and Target Energy Services for CIBSE (www.cibse.org.uk).

implementation through the gathering of feedback from users. It was also decided to continue to use the RIBA Plan of Work as a reference regarding project stage, as this is familiar to all design team members.

The results of the monitoring and follow up focus groups identified the needs of the next stage in this first phase of the research. The service had generated sufficient evidence of demand from the professions to merit continuation, however on the basis of one expert (the in-house researcher) providing support the service had reached saturation point. In order to allow the potential to be realised, it was now necessary to expand the network of specialist expertise to deliver advice more widely and to better support demand by improving access to CPD and other support materials. Further, by placing greater emphasis on recording the process it was felt that the ultimate goal of moving simulation into the design process could eventually be realised.

3.3 Development of a support infrastructure: Specialist networking

This next stage of research began in 1990. It continued much of the work of the previous stage, but expanded the research to explore the potential to improve the energy efficiency of buildings through the application of simulation in design practice supported by a mix of industry specialists and academic experts, rather than a single expert supported by a few tried and trusted researchers. Further, in response to identifying a need for additional resources to support simulation activities, in parallel with simulation support, a new work stream developed. This involved commencing the process of up-skilling the professions with regard to the latest design innovations by collating, digesting and disseminating information from the UK government's Best Practice research, development and demonstration programmes, now run by the Carbon

Trust (Carbon Trust 2008) with a view to supporting early stage design support enquiries, through case studies and good practice guidance. The Energy Technology Support Unit (ETSU) who recognised the potential additional benefits of an expanded service agreed to continue to joint fund the initiative with a total of almost £600,000 over three years.

The overall objective was to continue the work undertaken in stage one, but having identified an appetite for simulation, to now try to:

a) provide CPD training to raise awareness of energy issues generally;

b) improve availability of support by identifying additional specialists to provide support on a wider range of simulation tools;

c) to support this by making available Best Practice advice on low energy design from UK and other sources; and

d) to begin to address quality assurance issues relating to the provision of design advice, by developing standardised project records and procedures for recording simulation model data input and the resultant advice offered; with a view to:

e) create educational materials that could address some of the tool complexity and time related barriers to deployment in practice;

f) to continue monitoring and focus group activities to support the development of the project.

It was anticipated that this approach would facilitate the development of an industry that was ready to take on future environmental challenges supported by transparent procedures and systems that would provide the checks and balances necessary to allow practitioners to take on the work when the time was right. It was also important that these procedures should be suitably focused to allow both the re-visiting of projects further down the line, and for explanation of the processes involved to clients and building users as the designs evolved. In this way, the awareness and knowledge of practitioners and their clients could be raised simultaneously.

In order to support this activity, 15 modelling and simulation specialists were recruited through a detailed interview process that also served to identify the extent of expertise that existed in the construction industry in Scotland at this time. Emphasis on modelling and simulation remained a key theme, supplemented by the other forms of advice mentioned above.

The industry had responded well to simulation design support delivered through academic specialists, thus supporting the original hypothesis. The questions now were: how would the industry respond to a wider network of expertise? And, did the industry (and its client base) have the appetite to improve its low energy and environmentally responsible design expertise in order to better inform the process? Furthermore, what support was needed to facilitate this move?

In addition to an enhanced information transfer role, the research continued to support design teams in a similar fashion from 1990 to 1992 as it had previously done in relation to simple (free) consultations, i.e. as an activity undertaken in-house. There was a desire to expand the number, range and scope of detailed (subsidised) studies with the support of the recruited external specialists, and this represented a significant change in day-to-day operation. It was also envisaged that the additional support would provide greater scope to analyse the outcomes in order to assess the readiness of the professions to provide simulation advice from within the industry (if not as an integral design team activity), rather than relying totally on the support of academics.

In order to support the needs of the 15-fold expansion in the specialist base there was a need to devised and implement enhanced and improved information recording processes. A detailed Management Information System (MIS) was implemented for the recording of project details, ongoing project progress, recommendations, outcomes and to obtain feedback from customers on simple and detailed consultations by creating feedback forms that were automatically generated by the system. These were followed up by in-depth focus group surveys of users and the specialist support providers.

The MIS was based on *FoxPro*, a data-centric, object-oriented, procedural programming language released in 1990 by Microsoft in association with Fox Software. The last version of FoxPro (2.6) worked under Mac OS, DOS, Windows, and Unix (FoxPro 2001). The MIS as finally deployed was based on a review of the two variants of the consultation record documents used in the first two years of operation and with reference to forms developed by the London Energy Group (LEG) and the CIBSE Energy Reporting Format (see Appendix 3). Design questions were formalised to allow electronic recording and reporting with regard to types of enquiry and were consistent with the requirements of the Best Practice programme. This resulted in the development of new project summaries that accorded with typical government RD&D outputs from the Best Practice Programme. While the new system made information gathering more laborious, it provided more detailed information on many aspects of service benefits. Identified energy savings were recorded in kWh as well as monetary value, and by fuel type in order that the information retained its value into the future. A sample project monitoring form is also included in Appendix 3.

3.3.1 Monitoring Stage 2

The initiative continued to be monitored during this period and the results for 1990 - 1991were independently verified as before (Eclipse 1991).

In addition to continuing to monitor demand, user needs and expectations, value for money, energy saving potential and the effectiveness of delivering simulation through specialists, this second stage included exploring ways of improving the effectiveness of the service delivery and work practices through continuation of the focus group work undertaken in the previous phase.

During the two years from 1990 - 1991, 269 simple consultations were undertaken (a rate of 10 per month on average) and 52 detailed consultations: effectively doubling the work undertaken in the previous two years. Three quarters of the studies undertaken related to existing buildings (reflecting current economic conditions at the time), with advice based mainly on ESP-r but now expanded to include Tas, CYMAP, HEVACOMP and BREDEM. The annual energy cost saving resulting from these consultations was estimated at £360,000 per annum based on the reported feedback on level of uptake of improvements recommended by the simulation studies compared with the base case designs. This compared with Government funding of around £200,000 per annum, surpassing expectations, and indicated that if the professions (or perhaps their clients) were willing to pay the true cost, the initial outlay could be recovered.

At this stage of the research, to encourage uptake and to better inform potential customers, an awareness raising initiative was developed to inform the design community about the initiative. Newsletters and case studies were distributed to architectural and engineering practices to market and highlight the benefits of the available support (see Appendix 4). It was anticipated that the design community would respond to practical evidence of the benefits that simulation could bring through discussion of the issues addressed in a wide variety of typical new and refurbished building projects undertaken locally. A key aspect of these case studies was that they focused specifically on the impact that simulation had had on the projects analysed, supported by articles specifically relating to simulation advances, techniques and application in practice. The range of issues covered developed as knowledge of the service and the potential of simulation grew, with fairly simple or one-issue studies reported in the earlier case studies and newsletters, and a gradual move towards complex buildings and multiple issues emerging over time. In other words as the expectations and understanding of users developed, so did the service provided.

Although marketing beyond architects (through RIAS) was limited, knowledge of the service available within the rest of the design team, and by the building services engineering profession, was improved in part by the recruitment of the 15 specialist consultants many of whom were CIBSE members.

In setting up a register of specialists, the intention was to relieve the pressure on the in-house researcher, however, the allocation of work to the specialist consultants proved problematic, as equitable distribution of work required in-depth knowledge of each consultant's skills. In addition, there was an assumption that those seeking support would accept recommendations with regard to the allocation of specialist consultants. This proved naïve as in reality, the service's users often regarded themselves as being direct competitors of the specialist consultants operating in their fields. In practice this had two impacts:

- users were often matched with a consultant from a small sub-group within the 15 external Consultants who had distinctly different skills from the enquirer – e.g. simulation specialists; and
- a trend developed whereby specialist consultants brought work to the service on behalf of their clients on the understanding that they would receive a subsidy for the 'additional' services required to address specific energy/environmental issues.

Despite the fact that this had not been anticipated, these were understandable outcomes, in that simulation was still seen as new and risky, and has already been established, was not a service that clients were willing to pay the true market rate to use. Those who had skills wanted to test them in a protected way and those who did not were (probably) reluctant to expose this to competitors. In terms of the original objective of stimulating and meeting a demand for simulation through the provision of a pool of industry-based specialists and the wider objective of testing the market for simulation as a routine design team activity, both of the above issues would have to be overcome before either of these could be achieved.

The *ad hoc* approach to obtaining feedback from users adopted in stage 1 was formalised in stage 2 to allow a fuller evaluation of the potential for nationwide expansion of the service (see Appendix 3). This involved the adoption of classic questionnaire design practices to avoid open-ended questions, closed questions, ambiguity, vagueness, yes/no responses, and so on, as enshrined in the work of researchers such as Oppenheim (1983), and follow-up focus group and telephone interviews, in order to elicit as wide a range of industry views as possible.

Survey responses

Follow up surveys of users were undertaken to ascertain level of satisfaction with the scheme. Of 269 questionnaires issued 110 were returned. Based on simple consultation returns, feedback indicated that more than 90% of customers were satisfied with the speed of the response and just under 90% found the response helpful. This supported the conclusion that the expectations of users at the simple consultation stage were met. Based on a follow up focus group sample of 23 detailed consultations for which responses were received, 75% (17 of the 23) were satisfied with speed of response and 78% (18 of 23) with the helpfulness of the response – one having reservations regarding the speed of the response of the service but not about the value of the advice.

Number and type of enquiries

The number of enquiries received in these two years of operation was 269, around 10 per month. Of these, 52 had developed into detailed consultations with a further 30 in various stages of negotiation. The conversion rate had thus risen from 1 in 6 in the earlier stage to between 1 in 5 and 1 in 4.

The building types analysed ranged from regeneration of an existing mill and a farm building to a gallery and offices, to large-scale housing refurbishment projects or the performance analysis of a large local authority headquarters. The most common type of building on which enquiries were received was housing at 25% – both one-off new and large refurbishment projects (most of these related to the social/rented sector).

The remainder related to:

commercial/offices	13%
sport and leisure buildings and	8%
others (Medical, Museum, Restaurant, Courthouse, Police Station, etc.)	28%
general advice (energy and environment advice, etc.)	26%

The range of topics for which support was requested were as follows:

insulation	13%
passive solar and climate sensitive design	12%
general energy efficiency advice	12%
overheating problems and ventilation	9%
heating systems	9%
interstitial condensation	8%
building regulations	4%
energy costs and tariffs	4%
ventilation	3%
product advice	3%

heat recovery	1.5%
'green' issues	1.5%
general demonstrations of what simulation could do	1.5%
energy surveys, energy monitoring, targeting and management	1.5%
other	8%

This indicated a distinct shift in the type of enquiry from the previous stage, borne out by focus group discussions, from whole building and general energy issues, to the emergence of an interest in wider environmental/green design issues including the effects of decision-making such as site layout and orientation on indoor environmental performance, and issues surrounding the links between passive solar design and building materials and energy systems. In fact, new categories had to be developed in order to accurately record the widening range of interests. For very early stage, and simple enquiries, some of these issues could be addressed by the provision of the outputs of the government's Best Practice programme, but many required a second stage of support to test new design approaches through simulation. This indicated an evolution from advice on energy use and comfort to concern about the wider impact of buildings on the environment. Implicit in this shift was the growing recognition of the inadequacy of conventional design techniques. From this trend, the research concluded an emerging understanding of the complexity of the issues surrounding environmentally conscious building design. Designers were beginning to explore 'what if' scenarios and consequential issues. From the research viewpoint, this highlighted a perceived need for more complex single-issue studies and multi-faceted simulation requirements, possibly requiring more than one tool.

An analysis of the simple consultations revealed that enquiries came from the following sectors:

small-to-medium sized architectural practices	60%
local government officers	14%
engineering practices	10%
public sector architects	5%
large architectural practices	1%
other (e.g. householders, community groups, housing associations)	10%

This indicated that while public sector interest was still strong, private architecture practices were now realising the potential benefits – although it was not yet clear if this was driven by the architects themselves or their clients. On the client front however, 10% of enquiries had come from 'lay clients' and community groups – particularly housing associations through their committees and their architects. This was an important step forward in terms of creating a demand for the technology from outside of the traditional domain, and was seen as the first real evidence of a technology 'pull' rather than 'push' beginning to emerge.

The number of simple consultations that proceeded to detailed consultation was around 20% by the end of the monitoring of this stage (52 of a total of 269 consultations). This identified a growing desire to test ideas more thoroughly and again, rather than accepting the initial response, to ask *"but what if…?"*. A high proportion of studies related to existing buildings (75%). And an in-depth focus group analysis of a sample of 12 of these, which typified the range, revealed that advice was typically sought on:

solar control and solar heating issues	25%
energy savings	25%
heating systems and controls	17%
energy performance and energy management	17%
insulation and building environmental performance	8%
low energy design and natural ventilation	8%

Again, this confirmed the view that passive design was becoming recognised as having a key contribution to make in addressing energy and environmental performance, but in addition, there was a recognition highlighted from focus group discussion that new tools were required to assess the performance benefits of such new approaches to design.

The stage at which advice was requested was more difficult to ascertain during this stage, owing to advice being requested for a large number of regeneration and refurbishment projects. The lead-in time on implementation of works indicated that although many of these buildings were in use during the studies, the simulation support was essentially being undertaken as a feasibility study in most cases. The focus group confirmed that this reflected the economic climate of the time.

Feedback included an indication of the amount of the advice given that was incorporated into the project. The split was reported as follows:

Simple Consultations

Accepted and incorporated all of the advice	25%
Accepted and incorporated some of the advice	25%

Project delayed and thus unable to say	25%
Feedback form not returned	25%

Detailed Consultations

Accepted and incorporated all of the advice	33%
Accepted and incorporated some of the advice	33%
Project incomplete	25%
Feedback form not returned	9%

In other words those in receipt of free advice appeared less conscientious about feeding back or using information, perhaps reflecting the perceived low value given to free advice, although 50% did respond positively about using some, or all of the advice. This is supported by a stronger response rate of 66% of those paying for advice reporting that they would use some or all of the advice.

25% of users reported an intention to monitor the benefits of the advice received on capital and running costs. And the relationship between these two costs did not (at the time) appear to be a key reason for undertaking a detailed consultation.

Best estimates of the energy savings arising from the 269 simple and 52 detailed consultations undertaken during the two-year period of monitoring, indicated that typically, a simple consultation saved on average £600 per annum (20,350kWh based on the recorded fossil fuel/ electricity energy savings and average kWh charges of £0.04 electricity/ £0.025 fossil fuel as applicable at the time), while a detailed consultation saved around £11,300 (383,000 kWh) per annum. This resulted in an estimated total energy saving of £720,000 (24.4m kWh) (£130,200 for simple and £587,600 for detailed consultations), i.e. approximately £360,000 (12.2m kWh) of savings per annum. This compared with a one-off investment of £400,000 by ETSU (over the monitoring period) and equates to a simple payback period of just over 6 months on government investment. On this basis, the initiative was deemed highly cost effective, with a potential reaching well beyond the funder's expectation.

Four further points of note were that:

- estimated savings were not cumulative and would continue well beyond the first year of implementation;
- it was anticipated that users would implement similar measures on subsequent projects;
- the above does not include any assessment of capital cost savings; and
- during this time the simulation support service was proactively marketed (through publishing activities and seminars each with typically 100–200 delegates). The effects of these activities were not specifically monitored within the MIS. Although informal feedback indicated high levels of satisfaction and demand with these activities.

Thus, the potential for greater energy and environmental benefits from the application of simulation in the design process, beyond the scope of the projects on which advice was provided was identified, if not fully quantified. However, again no assessment of the relationship between the predicted benefits and the actual performance of the buildings on which advice was given was measured, although feedback on intention to undertake monitoring and/or post occupancy evaluation was provided on a number of detailed consultations.

Information transfer activity

In line with the development from stage 1 to stage 2, a number of information transfer activities were established to complement the simulation side of advice and design support. These included the following activities.

a. Accessing and processing RD&D results

Pre-publication and published reports, studies and information leaflets from government-funded studies were scrutinised and the results distributed in synoptic form. While this task proved onerous, the materials proved invaluable to the users of the service and to the specialist external consultants. From the materials provided, around 15 key references and texts were pre-digested and reproduced for regular external distribution – including a 20 page summary of the EU's Draft Passive Solar Handbook and texts for new-build and refurbishment of housing. All of these materials focused on early stage design, and from the research viewpoint contributed assisting practices to deal with basic energy conscious design issues, thus influencing the thinking that goes into projects before they even reach the drawing board.

b. On-line library

The sheer volume of materials made available through the research programme to its users by ETSU, BRE and BRECSU, prompted the cataloguing of these and other materials into an on-line system in *Dbase4* (Dbase4). This provided design professionals with access to a bibliographic, library of published materials categorised by subject area on a wide variety of energy and environment related topics. By mid 1991, over 450 items were catalogued and filed under 20 key headings. Appendix 5 provides a list of typical topics on which information was stored in the database including topics covering housing refurbishment, energy efficiency, benign building materials, passive solar design, energy management and control. The materials included Codes, Standards, Reports, Digests and Manufacturers' Technical Literature. This was regarded as a potentially unique technical resource for the service and allowed a quick response to general enquiries requiring rapid simple consultations. It also brought to the attention of the design professions the wealth of materials available, free of charge from a variety of sources. The issue of why designers in Scotland did not avail themselves of these materials already was raised, and although no definite conclusion was reached, the issues of poor access to information and the apparent lack of value of free resources were identified as possibilities. In order to highlight the work of ETSU, BRECSU, and other agencies, a number of high profile seminars were held at which relevant literature was distributed.

3.3.2 Recommendations

The allocation of work to external consultants was not as straightforward as had been anticipated in that client confidentiality and a lack of trust between commercially based specialists meant that the introduction of new or unknown experts to projects where a team already existed was not viewed favourably. This made it difficult to engage external specialists on projects other than in cases where an entirely new skill was required or where the specialist introduced a project to the service, in which case they fully expected to be the appointed as the independent expert. In other words some of the 15 specialists saw themselves as being in direct competition with one another, with the resultant effect that the in-house researcher remained overloaded. Notwithstanding these issues, this second stage of the research provided an opportunity to explore options that might lead to the greater use of simulation in practice – albeit at this stage in a protected way, through the use of specialists who were not part of the design team. The expansion of the number of specialists provided an opportunity to gauge the demand and the introduction of Best Practice materials from government sources provided early stage access to a variety of research outputs and created a conduit for these government publications in a time when access via the internet was not yet an option. Stage 2 of the research also highlighted the sensitivity of:

- maintaining an appropriate balance between marketing and promotion of the scheme and the workload generated; and
- balancing the division of labour between in-house and external specialist consultants.

In addition, as the amount of projects using the initiative grew, the need to develop quality assurance mechanisms for assessing and monitoring the skills and competencies of both in-house and external consultants, not to mention the advice given.

In the first stage, the key objective was to promote technology transfer through the use of simulation in the design process. In stage 2 the initiative was also expected to disseminate the outputs of the Best Practice and other government research programmes on energy efficiency, plus other recognised sources such as the outputs from European

Union funded programmes. This proved difficult to integrate. However, by the end of the full three years of the programme, a strategy had been developed to deliver the outputs of organisations such as EEO, ETSU, BRECSU, BRE, CIRIA and BSRIA in the UK as well as non-UK agencies such as the EC programmes CADDET and THERMIE. It was envisaged that this could be taken forward in a future stage.

Based on feedback on the degree of uptake of advice given, benchmarked against the design team approach before adopting simulation advice, government investment was judged to have been a highly cost-effective means of influencing design teams and reducing fuel consumption in buildings in Scotland, with a payback of less than one year predicted. The initiative was judged to be invaluable to ETSU, not only in terms of exploring the benefits of modelling, but also by identifying the underlying problems in up-skilling the industry and disseminating the government research that supported the simulation-based advice provision.

At this stage of the research, users were still largely protected from timescale barriers, although feedback on whether or not users were satisfied with the speed of delivery highlighted a tendency within respondents to expect results very quickly. However, at this point in time, this was balanced by the fact that general satisfaction with the quality of advice appeared to outweigh timescale issues. The other barriers to use of simulation in practice raised in section 2.2, such as the steep learning curve, credibility of results, trusting programs, and interoperability were not addressed directly in this phase, as users were still protected from making difficult decisions about validity of results, by their expert support. However the growth in the number of projects where multiple tools were required could in future give rise to interoperability issues, and reported focus group concerns over appointment of external specialists in terms of trust, commercial sensitivity, insurance liability and the perceived need for independent advice and support, all indicated that in-house adoption of simulation by design practice remained a distant dream. From focus group feedback, and a reported sense of confusion regarding who was responsible for the quality of advice given, it might be concluded that the industry was less comfortable with the approach to delivery described in this second stage of the research. However, from the research point of view, the retention of the cushion of a fully independent service was not sustainable in the long term, nor would it encourage the industry to rise to the challenge of developing an in-house capability. Notwithstanding the need to resolve all of the above, this approach was therefore regarded as an albeit difficult, but necessary stepping-stone to the embedding of simulation.

Finally, as the initiative continued to grow, the issue of quality assurance began to emerge more clearly. Initially, the most pressing requirement was to quality assure the selection of specialists to work with design teams in order to begin to break down the barrier of mistrust between client/ tool and specialist, but this would quickly expand into quality assurance issues related to model development and output/results in order to begin to build trust in the tools themselves.

3.3.3 Issues remaining

It was recognised that there was a need to develop greater trust if the decision to deliver simulation-based advice through industry-based specialists was to succeed. The only alternative to growing the industry's skills was that simulation would remain a service offered by researchers and simulation specialists to the industry. This was not regarded as a viable option due to a shortage of academic specialists with the required industry knowledge, and the fact that existing specialists of this type lacked the construction industry knowledge required to effect the paradigm shift required. However it was accepted that in the interim some form of hybrid approach to plug gaps in the system might be necessary.

Based on the growth in interest in wider environmental issues as evidenced in the shift in emphasis from general energy efficiency enquiries to more broad-based analyses of environmental performance and passive design approaches between stages 1 and 2, a need for specialist support on a more integrated level was identified. In the initial design stages, as had been evidenced in stage 2 of the research, government Best Practice and other RD&D (Carbon Trust 2008 (b)) publications were well placed to highlight case studies and new trends in thinking, particularly in the area of passive solar design, natural ventilation and exploiting daylight. The Best Practice programme was at that time little known or exploited by designers in Scotland and so it was felt that there was merit in making use of this as a source of CPD support, particularly during simple consultations and to begin the process of up-skilling designers in the art of simultaneous consideration of multiple design issues. In terms of furthering the research work, simulation was seen as having a crucial role to play in that, no other tools existed that could undertake the evaluations necessary to resolve building behaviours that did not rely on mechanical systems for environmental control.

The next stage of the first phase of the research explores the complementary impacts of improving general knowledge of green and passive design approaches and using simulation to resolve the design dilemmas thrown up by such approaches. In addition, this highlighted the need to establish the extent to which the existing specialist-base could respond to the need for an integrated approach, how it should be developed and the need for procedures to ensure confidence in partnering of specialists with users of the service. Moreover the question remained as to the ability of the available tools to respond to these needs, as until now thermal, for example, lighting and CFD analyses were at this time undertaken by separate tools and the assessment of the impact of one on the other was not yet possible without considerable effort.

3.4 A design support service: Integrated modelling

Stage 3 of the first phase of the research ran from 1993 and 1998, in addition to simulation support for energy related projects, the service expanded to meet the aforementioned increasing demands into wider areas including, ecological and passive design, materials issues, and renewable energy exploitation. This allowed the initiative to continue to provide a vehicle for the promotion of the government's Best Practice and Passive Solar programmes via workshops, seminars, information dissemination, access to case study material, through an in-house library of related design information and by providing assistance with interpretation of the relevance of state-of-the-art technology and design information including, potentially, the development of knowledge-based systems built upon the emerging outputs from the research. It was anticipated that by drawing on existing underutilised resources, an educational role would be fulfilled: increasing the confidence of designers to expand their knowledge of climate conscious and energy sensitive design on the basis of case study evidence of success.

Typically, simple consultations now comprised the provision of advice on issues such as:

- the appropriateness of design principles for low energy and climate sensitive design in relation to a specific project;
- site factors such as wind shelter, exposure and solar access;
- wider sustainability and materials issues relating to healthy buildings;
- the selection of calculation tools appropriate to particular design stages of a project; and
- in-house appraisals, both simplified and simulation-based, to assist with early stage design development.

This indicated a need to widen the scope of the research to encapsulate the bigger sustainability picture, necessitated an expansion into tools that addressed more than just energy issues, thus, in addition to in-house staff, with specialist knowledge of low energy design, the register of external specialists was expanded to around 45 with a diverse range of skills some analytical and some based on other relevant expertise who might team up with a simulation expert to provide a wider view. Given the focus groups' previously reported reservations regarding the potential conflicts between users of the service and the external specialists employed to provide the support, a need for a system for selecting and monitoring these relationships was identified to ensure that the project was not compromised. As with the previous stages, one day of support was available free of charge and if the need was identified, further work was funded, in part by the client and in part, by the government.

It had been established through the early stages of the research that the design professions were interested in the potential positive impact that simulation could have on the design of buildings, but that there remained barriers that prevented the routine use of simulation tools in practice. The objective now was to support the process of up-skilling the professions by moving simulation technology out of the academic domain, as indicated in Figure 3.1. The diagram indicates how by using specialists to undertake simulation outside of the design process, designers were provided with 'protected' access to simulation tools, thus underwriting the risks. In other words, a bureau service was provided, improving links between experts and clients seeking advice.

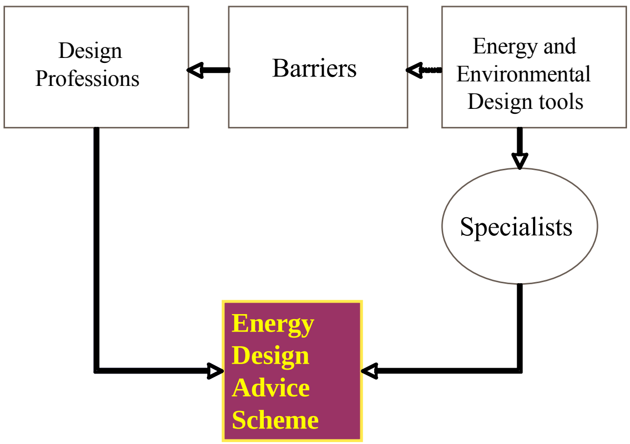

Figure 3.1 – the 'technology push' approach

3.4.1 Design support dissemination

To address issues such as energy benchmarking, environmental impact and sustainability, design teams need access to coherent advice. As a 'one-stop shop' for building performance advice, in this third stage, the usual information delivery routes - newsletters and case studies and online in-house library were adapted to include a wider variety of sustainability related topics. And as dissemination of government publications was now seen as a key educational role, the service needed to adapt and thus responded in 4 respects.

a. Information and Publications

Providing access to much of the accepted best practice advice available from recognised UK and other European research institutions was not in itself unique, as much of the information was already available from UK Government sources and the European Commission. However, through this initiative, users were directed towards materials specifically identified as being appropriate to the project under consideration; this extended to assistance with the interpretation and application of the information. And because the available information was often unsuitable for direct application, there was often a need to 're-package' it into forms suitable for dissemination through traditional routes. Some of this resulted in information papers on Passive Solar Design, Green Issues and Low Energy Design that were subsequently published by the RIAS in its quarterly Practice Information supplements as a regular contribution to the Energy and Environmental section. Sample documents are contained in Appendix 5.

b. Guidelines and Exemplars

The inclusion of wider sustainability issues in the design process made delivery of better buildings a more complex task, for which designers needed greater support. The role of the service thus increased to provide assistance with the interpretation and application of available case study and wider guidance in the real world of design practice. This was typically delivered through seminars and workshops, organised for both practitioners and specialists including:

- regular local meetings for specialists exploring state-of-the-art design issues;
- combined specialist/practitioner seminars on topics such as air flow, lighting, simulation modelling, indoor air quality, environmental emissions and renewable energy integration; and
- general and specific in-house simulation seminars for individual practices to promote advanced design tool uptake.

c. Case Study Material

The series of simulation case studies reporting on how the service had assisted design teams through the application of simulation within live projects continued, but these were re-toned to include wider issues going beyond the potential of simulation to save money through energy efficiency to include the wider environmental benefits of low energy and passive design approaches. Furthermore, by illustrating how simulation had improved the performance on fairly typical building projects, the intention was to illustrate the benefits that might be expected to accrue and to remove the misconceptions that form barriers to the deployment of simulation in design practice, as a longer term goal. For sample case studies see Appendix 6.

d. Newsletters

Regular newsletters continued, but these were restyled to include these wider issues, highlighting key projects across the UK and providing feedback from users of the scheme to encourage greater uptake of the service. The range of projects covered in these newsletters is illustrated in Appendix 6, extending from the refurbishment of a derelict theatre, through a zero energy ‘eco-centre’ to a visitor centre built entirely of local materials on a remote site in Scotland to a naturally ventilated school by one of the leading sustainability focused architecture practices in the UK at the time. This indicates not only the spread of projects, but also the fact that even those with sustainability and low energy design skills valued what the service could offer in support. The newsletters were distributed to all architects and building services engineers registered with ARCUK and CIBSE in the UK and also to major building client bodies, and were supplemented with brief, postcard-sized case studies.

Despite the availability of an abundance of information and a spectrum of simplified to detailed design tools, the direct application of information and technology within live projects is not straightforward. While statements about 'consideration of local climate’ or 'making use of fabric thermal mass’ appear self explanatory, establishing a simulation study to examine such issues is non-trivial and site or project specific. The need for new ways of transforming data into useful information was a recurring conclusion from the more detailed consultations undertaken, as first raised in section 2.2. This lent credence to research at the time that was focused on solving program users’ problems through the creation of intelligent front ends (Byungseon & Degelman 1991) and data interchange facilities to allow program interoperability. These are key issues, and are further explored in section 3.5, pp101. The newsletters also began to highlight the multiple issues that were now being considered, and demonstrated to potential users, that, although fully integrated tools were not yet available for in-house

use, there was scope through the initiative to work with more than one expert at a time in order to make the required judgements on a variety of issues simultaneously. The logistics of this are discussed in the next section.

3.4.2 Expansion of low energy design expertise

Stage 2 highlighted the need to build confidence in selecting and pairing specialists and users of simulation in terms of compatibility, quality assurance and for a better understanding of how the delivery of simulation-based design advice could be made more effective.

In order to make the best use of the expanded team of experts a quality assurance framework for selection of projects, project team partnering and monitoring of progress and outcomes was required. At this point in time, although recognised as a fundamentally important issue, the perceived immediate need was not to quality assure the advice given, but to ensure the best possible process in order to protect the interests of all involved. It was envisaged that the in-house researcher would play a key role in managing the process and assisting interpretation and application of results. At this point in time there were emerging industry standards for quality assurance procedures (BS5750, ISO9001). These were found to be applicable to the development of procedures for the appointment and management of simulation in practice and were therefore adopted for the development of the required framework.

Within the devised framework, every project was broken down into a series of steps as indicated below.

Initial advice & support

This involved a two-stage process and was undertaken in-house. It involved an evaluation of the project and the problem being presented, in order to gauge the level at which support was required/ could be made available, depending on complexity and available/required resources, and then selecting the most appropriate specialist to undertake the work.

Project evaluation

When a project team requested advice, in order to evaluate the enquirer's actual rather than perceived needs, a preliminary assessment of the key design issues was made, offering initial advice and design guidance based on previous project experience, application of best practice guidelines, use of simplified design tools and so on. For example, an enquirer may state that the problem is one of summertime overheating, but this might lead in many directions - from a study of solar shading and control, through materials selection issues and fabric mass to a study of internal gains and occupancy issues. The designer may also be focused on worst-case scenarios and mitigation, when in fact the worst case may never arise in practical building use terms. This early stage evaluation also included a judgement as to the merits or otherwise of a second stage. If simulation was deemed appropriate, project requirements were assessed against the simulation capabilities available from specialists and the most appropriate consultant was recommended.

Selection of specialist consultants

Anyone was eligible to apply to become a specialist consultant, but not all were accepted. The scheme aspired to ensure that those selected covered a wide range of specialist fields and offered specialist advice that was not readily available elsewhere. A rigorous application process demonstrated that the organisation was *bona fide,* with a proven track record in a relevant specialist field, but even then, acceptance on to the specialist register did not guarantee work from the service. Mutual trust had to be developed and it was essential that the specialists provided evidence of commitment to the aims of the scheme and continuous professional development activity.

Selection of the most suitable specialist to undertake a study was a difficult task. In the early days selection relied on previous experience or knowledge of the external consultant based on the best judgement of the project's in-house researcher. There was also scope for more than one specialist consultant to be appointed to a project to provide a complimentary balance of skills. The in-house researcher's involvement in the process of advice delivery from the specialist consultants was seen as paramount in terms of quality assurance and service credibility. The focus groups had highlighted a need for greater transparency, and so the procedure was formalised as follows, with consultants selected on the basis of:

- the project requirements compared with the skills of the specialist;
- the potential for a good relationship with the enquirer and the avoidance of perceived commercial threat;
- in-house experience in terms of the specialist's performance on previous projects (e.g. customer requirements in terms of timescale against the specialist's ability to deliver); and
- the degree of interaction sought by the customer (hands-on, hands-off, and so on).

Matching of projects, project teams and specialists was seen as critical to success in that, the more harmonious the relationship, the greater the focus on the project in-hand, and the greater the chance of a successful outcome for all involved.

Consultant support

Specialist external consultants were supported with training and seminar programmes, providing the opportunity to exchange ideas with others with complementary skills. These commitments helped build a relationship between the service, its specialists, and users, facilitating the matching of appropriate skills with client needs.

Analysis definition and project costing

Understandably, designers are often reluctant to use simulation in cases where they have no concept of what outcome to expect. This highlighted the need for clarity in defining the project from the design team's viewpoint, clarifying the key issues, deciding what should be simulated, why and what the benefits might be.

Practitioner and specialist agreement

At the outset of a consultation agreement, both client and consultant were required to provide details of the project. For the purposes of monitoring, it was important that adequate project details were provided to allow a meaningful assessment of the outcome of each study. On agreement of costs, but prior to the analysis proceeding, the client and external consultant signed an agreement confirming the right to publish the results. Over the 10 years of the research, a database was developed to store repositories of case studies of a comprehensive range of buildings, allowing users to scan ranges of performance for similar building types. During the period of the research, the need to rely on previous experience, supported by the available publications for generic building types, did not offer adequate scope to test the robustness of innovative design ideas in specific locations (McElroy 1996).

Technical appraisal through simulation

Once a specialist was recommended, an agreement on the scope and cost of the study was drawn up with the support of the in-house researcher. Registered specialists supplied day rates for specific types of analysis, and projects were costed in terms of the person-days resource required to undertake tasks agreed with the client and supervised by the in-house researcher. If a quotation was accepted, a project team was formed. To optimise the return, it was recognised that interactions between the team should be co-ordinated, and ideally this meant that someone on the team had to be cognisant with both design and modelling issues. An appropriate mix requiring, for example, a project manager and modeller from the specialist team, one or more members of the design team, the project initiator (e.g. client representative) with the in-house researcher in the role of co-ordinator.

Model calibration

While modellers may be confident about the validity of the results produced by a model, there is no developed system whereby this confidence can be passed to a client. This was a key point raised by the focus groups when discussing the use of external specialists. There was therefore an opportunity to develop an ongoing role for an independent scrutineer (at that point in time a role fulfilled by the project researcher), able to ask appropriate questions of the modeller with regard to model calibration and able to pass information back to the client: checking the appropriateness of a particular simulation program for a particular task; assessing the probable credibility of results and bringing in existing benchmarks for similar projects where results were not as expected or providing comparisons with recognised benchmarks such as performance indicators, or existing measured data for similar building types.

In the context of the research, a live database archive allowed the additional advantage of scanning of ranges of performance for similar building types and the option of modifying certain features to allow re-assessment if required - thus providing an opportunity to create dynamic performance indicators. This and other aspects of monitoring are reported later in section 3.4.3.

Design parameter uncertainty

An important future issue facing users of simulation is uncertainty. In the context of innovative design, it is the risk element of the design that designers need to be able to test in order to push forward design boundaries. Only when the uncertainty of a parameter is known, can the associated risk be determined. Simulation can handle the effects of uncertainty, but only if users can attach uncertainties to model parameters. The requirement then is to attach values to these unknowns. It was envisaged that the now extensive project database might cast some light on this issue in future. The issue of uncertainty is not resolved through the reported work, but is discussed at greater length in section 3.5.4 and in chapter 4, section 4.3 and 4.4.1.

Project monitoring and technical support

Whilst the research supported the integration of simulation in design and the advancement of knowledge within the professions, it is important not to confuse *use* of simulation with *integration*. Accordingly, support was provided in the development of pertinent questions, selection of an appropriate approach, and access to required information in order to support a design profession that was not yet wholly familiar with the technology or the appropriateness of one tool compared with another.

Audit trail and standardised reporting

External consultants were required to maintain an audit trail, which, together with copies of all models were maintained in an archive for up to two years to allow projects to be revisited as and when required. This applied to all projects although the extent of this varied depending on the nature of the study. Ongoing involvement allowed examination of the simulation approach in each case, enabling feedback to users in respect of the methodology adopted, and facilitating the development of the procedures to inform future use in practice.

A standard reporting format was also developed, whereby interim and final reports for simulation projects were prepared using standard templates allowing (as far as possible given the range of projects) direct comparison of all building studies undertaken within this stage over 5 years. These included blank templates for all design aspects available from the model - even if these did not form part of a particular study, thus allowing for phased studies and providing for across the board comparisons.

Sign off procedure and feedback

At the end of a study, a sign off procedure confirmed that all parties accepted the outcome of the study. This provided a final opportunity to obtain feedback on the customer's impression of the exercise. Information on promptness of delivery, relevance of advice, level of uptake in terms of incorporation into the design, the level of understanding and engagement between the parties involved, and so on, was requested, in order that information fed back into the system was a true representation of what actually happened. This was a critical part of the process, as all energy and environmental benefits predicted by the process had to be validated from the client's viewpoint. Support funding was not released until a feedback pro-forma was completed. This offered the following advantages:

- the user was given the opportunity to influence the running of the support service with respect to meeting the needs of the real world;
- the user was given the opportunity to comment on the value of the design exercise as a whole;
- the support service was given the opportunity to compare the predicted benefits with client expectations and the implementation of recommendations; and
- the in-house researcher and the appointed specialist were given the opportunity to compare theory with practice.

Based on the concerns raised in focus group discussions with users, the above provided users with a degree of comfort in terms of providing feedback opportunities within the process rather than at the end, when it was too late.

As a result of all of this activity, the need for a quick turnaround and flexible access to specialists were identified, as growing interest from users resulted in greater demands in respect of the number of questions asked and the number of design variants put forward. Thus the research was now benefiting not only individual design team members but was beginning to encourage collaborative working as design teams came together to pursue better solutions. There were even a few, if as yet isolated instances of a team of specialists: lighting and thermal modellers, plus the in-house researcher, spending a day inside a practice to experience real-time demands first hand.

The initiative was now dealing with over 150 enquiries per year and from a research viewpoint this quantity of projects provided an opportunity to:

- identify that although the general principles were understood, practice still had difficulty with turning information into informed design decisions (thus providing both a need to identify and address educational shortcomings and emphasising the role that simulation could play in providing answers), see section 3.5 (pp101 – 111);
- confirm the importance of early decision making in terms of site, orientation, form and fabric on the performance or delivered outcomes at critical stages in the design process where advice will have maximum impact on energy use (thus identifying a need for easy to use, effective early stage design support tools);
- identify patterns in energy advice sought, advice given and advice adopted; (thus contributing to the potential for development of knowledge-based advice systems for use in-house by designers).

These issues are further explored in the following section and in section 3.5. However, at this juncture it is important to note that feedback from programs on the possible or probable causes of results were not available at this point in time (1997), and analysis of all aspects of input data versus output results was a laborious but necessary task.

3.4.3 Monitoring stage 3

By this time over 1200 enquiries had been made to the service and of these over 300 had evolved into detailed simulation studies. This put at the researcher's disposal a substantial amount of data for analysis. An in-house evaluation of 250 projects was undertaken to evaluate the effectiveness of the service. The primary objective, was to produce advice that would support all those concerned with the delivery of a more sustainable built environment through the promotion and assisted application of simulation and recognised RD&D and best practice advice.

The management information database included details of estimated potential energy savings arising for each project, collated into an automated report, including details such as project type, size, value, and the stage at which the customer approached the service. This information was used to undertake statistical analysis with a view to demonstrating the demand, impact and cost-effectiveness of the application of simulation in providing useful design support, energy savings and other environmental benefits.

The management information system was by now well-developed and as a result it was possible to research the impacts of the initiative in a wide variety of ways as follows.

a. Building Types

Buildings analysed were categorised according to the Energy Efficiency in Buildings series, as published by the UK Department of the Environment Transport and the Regions (McElroy *et al* 1997). The breakdown is shown below:

Offices	18%
Housing	16%
Schools and Higher Education establishments	15%
Libraries Museums & Galleries	9%
Recreation & Leisure (sport, theatre, etc.)	8%
Factories & Warehouses	7%
Healthcare	6%
Hotels & Multi-Residential	4%
Other (e.g. Retail)	15%

It should be noted that the reduction in the number of housing projects by proportion (from 25% previously to 16% in this stage) reflects the application of a rule change whereby a minimum floor area of 500 m^2 was instigated in order to maximise energy saving potential by ensuring that a disproportionate amount of time was not expended on one-off house designs. This did not affect the message inherent in the data.

These results indicated that while the interest from the public sector remained high, with housing, education, recreational, leisure and healthcare facilities making up over 50% of the total, the private sector was not far behind, including a number of large prestige office, retail and transport projects which offered high potential energy and environmental benefits. On the other hand, public sector projects although in the main related to existing buildings, highlighted the local authorities' determination to improve maintenance and to make the most of their existing stock. This, and the general nature of the split are discussed in greater detail within the remainder of this section.

b. Questions asked and advice offered

Typical questions ranged from advice on heating system selection or insulation levels to integration of renewable energies and effectiveness of complex passive solar features in large commercial buildings. The analysis of the advice offered indicated that the majority of questions related to:

building fabric	25%
heating systems	20%
ventilation	18%
fenestration	18%
other issues – form, orientation, siting, etc.	19%

It should be noted that many of the design questions asked were becoming multi-faceted and that the MIS facility required that a key issue relating to each was recorded. Given that this stage of the research was in-part instigated by the multiplicity of design issues for which advice was now being sought, this approach to recording arguably undermines the stage 3 objective. However, at the time the wider information was recorder in text/ dialogue areas within each project record – with a view to extracting this if the need or opportunity arose – e.g. for the purpose of case study development or report writing in order that the rich nature of this material was not lost to the research.

Typically, school and office project enquiries related to energy performance and comfort, but as time went on daylighting, glare and solar control began to emerge as associated issues. This resulted in two types of model emerging for these typically repetitive, modular building types: one of the whole building for annual energy consumption studies and a second, more detailed model of a typical room from which design variants to explore multiple issues could be generated.

A typical scenario was that architects at this time were particularly interested in solar control glazing and external shading systems to address summertime overheating and glare, however, they tended to have a simplistic view of this as a solution to the problem (one that had often been inherited in an existing building), and gradually saw real benefit in the use of simulation to illustrate the potential impact on internal temperature and daylight quality for example.

Interest in energy performance, solar gain, solar control and glare in such projects identified a clear need from the industry for better-refined tools to meet these emerging needs. In the main, this need related to schools and offices where designs were fairly modular, and so although the industry was expressing a clear need for integration, complexity of form was not seen as so great an issue. In fact, at this time the need was met by using two models – one to undertake the thermal study and another (research model with no graphical output) for the lighting analysis. The demand for such analyses was high at around 30%, and so this sent a clear signal to the industry regarding what users wanted.

The fact that questions asked were beginning to relate to a variety of questions was significant. At this time tools were almost entirely focused on one aspect of simulation (thermal, lighting, CFD, etc.), but industry users clearly recognised a need to explore the combined effects of a variety of factors, raising not only the issue of integrated modelling, but also the need to be able to compare results simultaneously within an integrated performance view. The emergence of this need was timely, as the European COMBINE Project, which would go on to explore tool interoperability and results presentation issues was to commence shortly thereafter (Augenbroe 1995).

It was encouraging to note that a high proportion of projects (around 50%) were now requesting simulation support at the feasibility stage where decisions will have the greatest impact on energy use and environmental impact. This related to an increase in the number of new build projects requesting simulation support. It also highlighted an emerging need for tools that supported early decision making, before building designs were fully formulated.

Architects remained the most frequent users at 35%, especially at the early design stages. Some requested advice on account of their own interest in the possibilities, others, because their clients had requested a more detailed approach – indicating that the importance of energy and environmental impact of buildings was now becoming more widely appreciated generally. This group was the most likely to seek advice at the inception stage, typically of site and shelter issues or materials and avoidance of overheating if the site location was fixed.

Local Authorities were the second largest clients at 15%, although for this group questions often related to existing buildings and refurbishment projects. This client group were the most likely to undertake detailed and multi-faceted analyses, relating to the fact that they have ultimate responsibility for the performance of their building stock. They also demanded support for whole building energy performance predictions and upgrading and controls advice.

Building services and energy consultants represented a further 7%, and generally sought advice on adopting passive energy approaches, such as natural ventilation and solar utilisation, and the interaction of such approaches with fabric and glazing options – in other words, on issues that went beyond typical plant sizing calculations and which could not be addressed by the emerging computer-based calculation methods used by engineers at that time.

The above information was fed back to the industry to help identify current and future trends in advice sought and simulation program needs now and for the immediate future.

c. Cost of detailed analysis

The cost of procuring simulation through the initiative ranged from £500 to £25,000. In order to qualify for a high level of funding, it was necessary to demonstrate that the potential energy benefits would justify the level of financial support. Projects that attracted such assistance tended to be large and involved a degree of risk. For example, simulation was employed to analyse internal temperatures within the new, Niels Torp designed British Airways Headquarters building, which incorporated self-shading features and optimised daylighting and natural ventilation despite its location near Heathrow Airport. The project comprised several long narrow finger-like buildings linked by an internal street, and the intention was to avoid mechanical cooling. Simulation was used to study the combined effects of fabric mass and self-shading to optimise plant requirements.

The study resulted in plant cost savings of the order of £350,000 for an overall study outlay of around £20,000. More typically, the cost of a study was of the order of £2,000 - 7,000, depending on the estimated potential energy benefits.

There was by now consistent evidence of a considerable uplift in the use of simulation modelling, which was by now influencing some of the UK's most significant projects, including:

- Waterloo International Airport – Bulk air movement studies to minimise heat losses.
- Phoenix Building: BRE – Stack ventilation assisted by photovoltaics and daylight study.
- American Air Museum at Duxford – Daylight analysis.
- Waterfront Conference Centre, Belfast – Displacement ventilation design support.
- Birmingham Symphony Orchestra – integrated simulation for low energy design.
- Arc Pavilion: The Earth Centre, Doncaster – simulation to minimise energy demand.
- Office: Victoria Quay – daylight and mixed-mode/ natural ventilation analysis.
- Offices: British Airways, Heathrow – Daylight, ventilation and overheating analysis.
- Refurbishment: Festival Theatre, Edinburgh – Complex, mixed-mode ventilation study.
- Regeneration (façade retention): GPO Building, Edinburgh – use of simulation to demonstrate compliance with Scottish Building Standards Carbon Emissions Method.
- District Heating: 288 flats at Hutchesontown, Glasgow – Major refurbishment of fabric combined with environmental (internal and external) improvements and district heating with potential to expand to over 500 dwellings and adjacent services.

– Finally, the installation of renewable energy technologies on the refurbishment of The Lighthouse building in Glasgow was the first time that simulation had been used to explore the combined effects of a variety of traditional and niche applications of renewable energy systems (building mounted wind turbines, photovoltaics, (for electrical and heating energy), daylight utilisation and transparent insulation façade) and in a city centre location in Scotland.

A further measure of the growing effectiveness of the initiative for the delivery of simulation to the professions was the impact that it had on building construction at the national scale. Records indicated that towards the end of 1998, 12% (by capital cost value) of all building projects in the UK were benefiting from simulation support through the initiative. This figure was based on information gathered from the then UK Department of Environment, Housing and Construction Statistics 1992 – 1996 (ETSU 1998a).

In respect of the promotion of recognised technical information and advice, a survey of users and non-users of the simulation support service reported a higher than average awareness of key sources. Moreover, the dissemination materials supplied by the initiative were dispersed throughout their practices and were thus influencing up to 30% of all work undertaken by these organisations – far beyond the impact gained on the specific project for which they had been supplied. Furthermore, those practices that had used the service reported that the advice received was likely to ensure that 75% of work passing through the office would exceed the 1998 Building Standards (Scotland) Regulations minimum requirements (ETSU 1998a).

Cost effectiveness - energy saved

The MIS facilitated the monitoring of the effectiveness of the scheme in terms of value for money. For every £1 spent by the Government and those procuring simulation support, £30 of equivalent energy saving potential was identified as a result of simulation and feedback on the associated advice given. The figures were arrived at through evaluation of simulation modelling studies and energy audits in the case of detailed consultations and by making an estimate based on the potential as outlined in the most appropriate BRECSU Best Practice publications at the time (now operated by the Carbon Trust (Carbon Trust 2008)). The benchmark was the building as presented prior to analysis, compared with the outcome of any study undertaken – set against good and best practice benchmarks as set by BRESCU for the appropriate building type. The savings amounted to a potential energy equivalent to around £25 million saved per annum, based on specific information received for each project analysed, highlighting the huge potential impact that simulation could have. However, this positive outcome had to be counterbalanced by the facts that:

a) simulation advice was heavily subsidised by government and

b) there was as yet no evidence that the industry was willing to pay the market rate.

Follow up feedback forms completed by users (see Appendix 6 for sample forms) indicated that of the advice received, an average of 65% was implemented in the final project, resulting in a net annual energy saving of over £16 million (excluding replication potential and the cumulative impacts of these projects projected forward in time). The resultant CO_2 emissions reduction and kWh savings were estimated at 285,000 tonnes and over 635 million kWh annually, based on advice reported by design teams on implementation rates and proposed fuel mixes. Further details on the assumptions made are contained in ETSU report S/T1/00133/REP – Energy Design Advice Scheme (EDAS) Operations and Achievements 1992 – 1998 (ETSU 1998a).

Furthermore, it was estimated that the cumulative effects in terms of energy saved to 2008 would amount to over £172 million (not including fuel price inflation, but accounting for deterioration in performance and replacement of components reaching the end of their natural lives) and a reduction of around 2 million tonnes CO_2 (4,500 million kWh) over the same time period. This compares with a cost of £6 million government support on a UK wide basis centres over 7 years. In terms of cost effectiveness, it can be concluded that offering simulation support with government subsidy in this way had been successful. In research terms, prior to delivery of design support through this initiative, best government estimates of the effectiveness of previous initiatives were based on an approximation of 10% saving in CO_2 for 10 out of every 100 Best Practice guide distributed, backed up by monitoring of advice given in specific case studies.

Key remaining issues for the research were that although the industry recognised the benefits, there was as yet no evidence that they would pay the market rate, and the potentially linked issue of a lack of recognition of the potential for everyday application to everyday projects was as yet unresolved.

3.4.4 Recommendations

Surveys of users carried out within the focus groups showed that the industry was of the view that the initiative had been successful in providing initial design advice. 90%

reported that support had been provided quickly enough and that the answers were helpful. In the case of detailed consultations, final figures showed that around 80% were satisfied with the quality of information. In terms of the research, the case is made that this high level of satisfaction reflected the industry's realisation of the value of the design support.

Over an eleven-year period, integrated modelling had gradually been established as a valuable source of simulation support and independent advice on energy and environment related aspects of building design. Moreover, it was concluded at this stage that modelling had a key role to play in the performance evaluation of high profile and prestige building projects. In 1998 government withdrew funding after almost twelve years and the delivery of design advice was centralised as part of a larger initiative.

By this point in time, in 1998 the associated research had achieved one of its key objectives in that the initiative had raised awareness within the design community of the need to reduce energy use in buildings, the potential role that simulation could play in achieving this and how this could be effected through a simulation support initiative, linking designers/building clients and modelling specialists. Work to date had provided hitherto unavailable access to simulation tools as a means to answer some of the more complex questions that a 'sustainable' approach to design introduced. Before the advent of this initiative, there was no way of answering such questions, other than to construct the building and hope for the best. Now it was widely accepted that simulation defined a best practice approach to the assessment of design performance (CIBSE 1998). And through this research, it had also been established that the needs of practitioners vary, depending on the stage of the project, the information available, the number of options being assessed and the level of detail required. All of this had served both the design and simulation professions well, by bringing the viewpoints of practitioners and specialists closer together.

This stage of the research addressed barriers related to quality assurance when appointing specialists to undertake simulation on a client's behalf, encouraging designers to value simulation as an integral part of the design process, and recognising the benefits of using simulation to answer complex environmental questions that cannot be undertaken by single aspect, simplified tools. In this respect it was successful. Although it addressed barriers related to understanding the process, trusting outputs and the credibility of results, evidenced by the growth in projects using the service, and the high level of uptake of recommendations, it did not address issues associated with cost, timescale and the steep learning curve associated with adopting a simulation approach to design.

With regard to the next stage, now that simulation was becoming more widely accepted, it was necessary to explore how simulation could be delivered cost effectively to the professions without government support and to address the issue of simulation being seen as something of value to everyday projects.

Before the project was finally wound up, and in order to identify what still needed to be done to assist the professions in adopting a simulation-based design approach, it was decided to analyse the associated case study material with a view to defining a quality assurance procedure to control the deployment of simulation as an integral part of the design process. Otherwise the key benefits of the research could have been lost as a new government initiative took over.

3.4.5 Issues remaining

The adoption of a procedure for selection of specialists assists clarification of key issues, which can greatly affect the simulation outcome. But this is only part of the answer, and by now simulation was becoming recognised as a necessary part of the design process for some if not all projects, however, the client/ specialist approach to deployment adopted by this initiative gave rise to bottlenecks and delays, which caused frustration for designers and specialists alike. Of greatest concern was the fact that simulation was seen as a requirement for the largest and most complex projects, and without procedures in place, the risks of misuse and misinterpretation were high. Accordingly, the need to develop a quality assured methodology for the application of simulation was seen as the next most pressing issue.

It was clear that in order to achieve the ultimate goal, (moving simulation from the domain of the specialist into the hands of practitioners) there was a need to develop an appropriate procedure for the successful delivery of simulation-based design advice in order to begin the move from specialists to a practitioner activity. As the shift in delivery would not happen overnight, a general consensus existed in the first instance, that this procedure should be suitable for use by specialists and practitioners alike.

Another issue related to benchmarking. The repository of archived projects stored a wealth of well-tested building models for a wide range of building types. This offered a vehicle to study the impact of program modifications on real projects, thus providing the future opportunity for comparisons with theoretical test results. Benefits of this would be twofold: modellers could take advantage of an opportunity to test new versions of programs against real projects that had been simulated using earlier versions in the knowledge that results should correlate and, secondly, advantage could be taken of an opportunity to test new tools and new tool versions against existing buildings for which actual energy performance information existed.

In order to progress the use of simulation in practice, practitioners would ultimately have to learn to use tools on their own, unsupported. Based on observations made, recorded and analysed from over 400 projects, simulated over a ten-year period, the next section outlines the next stage in developing quality assurance procedures to facilitate the eventual routine use of simulation by practitioners. It was not expected at this stage that this simulation methodology could be adopted without the input of specialist support, rather, it was designed to provide appropriate insights and checklists that could gradually be integrated into the design process as practitioners gained the required skills.

3.5 Development of a simulation methodology for use in practice

The project database established over the first phase of this research, provided case material that was used in the development of a methodological approach to the use of simulation within the design process. In particular, the development of common approaches to problem definition (i.e. translating design questions to specific simulation objectives - as discussed in section 2.2.3) was devised – supported by case study analysis, interviews with users and general monitoring of the outputs of the research. The objective of this was to ensure meaningful answers and predictable results from the application of building simulation in practice. The outcome of this work is embedded within the CIBSE Applications Manual for Building Energy and Environmental Modelling (CIBSE 1998, Strachan *et al* 1997)). The procedure was tested using material distilled from a wide range of design studies relating to diverse projects in order to illustrate its adaptability to modelling at various levels of complexity. In all of the studies selected for detailed examination, there was a need to resolve design questions that could not be addressed by traditional methods.

Issues considered in the development of the methodology included:

1. Identification of *design team objectives*.
2. Typical range of *design questions* asked.
3. How these design questions are translated into specific *simulation objectives*.
4. *Common procedures for undertaking simulations* (e.g. *input data*; creation of *reference models* against which parametric variations are undertaken; phased studies; iterative procedures; frequency of client/simulation team meetings etc.).
5. *Interpretation of results* and client *reporting requirements*.
6. A description of the final design and how the simulation exercise influenced this.
7. A brief discussion of other issues that could have been investigated by simulation but were not included in the study.

Typically, the approach to simulation deployment at this time relied on specialists working with design teams, and although the development of the procedure drew entirely on this ‘hands-off’ approach, a methodology was developed with in-house use in mind, informed by the observations made within the previous research phases and taking on board the potential of use in everyday practice. This procedure and key considerations for use of simulation within the design process is outlined below and the specific application of the simulation methodology to one project, which was selected based on the fact that it covers a wide range of issues within a number of interrelated stages is elaborated in section 3.6.

Before a simulation exercise can start, it is necessary to clarify the design questions to be addressed and to translate these into simulation objectives. The next step involves preparing appropriate models, undertaking simulations and finally interpreting the results prior to making decisions on design modifications based on the outputs. The methodology developed provided:

- procedures for undertaking assessments against defined performance objectives;
- checklists for users of simulation programs;
- guidance on sources of input data;
- guidance on creating models for specific performance appraisals;
- guidance on results analysis and reporting;
- guidance on quality assurance checks.

3.5.1 Identification of design team objectives

Asking the right questions at the right time is critical in terms of getting the most out of a simulation-base design analysis. Typical questions posed by design teams will vary according to the stage of design development, for example:

- feasibility and outline proposal stage: *does the building require air-conditioning?*
- scheme design stage: *are the building orientation and glazing distribution reasonable?*
- detailed design stage: *which control strategy provides optimum energy savings?*

The questions posed above are typical of the reactive nature of the design process at the time and are not necessarily the questions that a simulation expert would ask at the same stage, which might be more proactive, such as those listed below and in 3.5.2.

Early experiences from the research indicated that most designers sought advice in the middle of the scheme design phase and were almost entirely looking for quick answers for energy and environmental performance issues – *how much energy? what summertime peak temperature? will there be condensation? how much money can we save?* But as the benefits became apparent, and approaches were made earlier in the process, the questions matured - *how can I avoid summer overheating? can we recover heat and re-use it elsewhere in the building? what passive measures can we employ to avoid air conditioning?*

Typical range of design questions asked

Typical design questions that can be addressed by simulation might include those listed here and as identified in the CIBSE Applications Manual AM11 (CIBSE 1998):

- what are the peak plant loads, when do they occur and what are the main influencing factors?

  supplementary question: what is the variation in operating hours between using optimum start control compared with a seasonal pre-set condition?

- can natural ventilation be used to provide fresh air requirements and reduce overheating risk or is a mechanical solution required?

  supplementary question: what system would be the most efficient in providing year round comfort?

- what are the effects of features such as atria, sun spaces or advanced glazing on thermal comfort, energy consumption and lighting quality?

  supplementary question: what will be the effect of increasing the wall insulation or going from open-plan to modular offices?

- what benefits can be expected from different lighting control strategies?

  supplementary question: what would be the energy saving implications of using lower general lighting levels, supplemented by task lighting?

- what are the energy consequences of non-compliance with prescriptive energy regulations?

  supplementary question: are potential capital and operating cost savings significant enough to warrant a more detailed investigation of low energy options?

The early stages of the research had revealed that designers often considered simulation as a problem-solving tool, and thus, sought advice only once the design had taken shape – *how do I make this into a low energy building? – I need to make this building sustainable. – The client wants this building to be naturally ventilated.* Based on the model developed within the quality assurance procedure for selecting consultants, in order to avoid using simulation to alleviate problems that designers create themselves, all projects should commence with a detailed team discussion of the strategy to be adopted and the degree of detail necessary to answer the key questions posed with the resources available. Simulation should be considered as part of this process. To maximise the benefits derived from a simulation exercise, the team should include someone who understands design issues and simulation capabilities in order to co-ordinate the interactions between the client, design team and simulation specialist(s).

The simulation model should be no more complex than required to answer the question(s) asked, and this requires that design questions should be asked in terms that can be addressed by simulation. The benefit of knowledge from previous projects can be used to inform new project analyses, recognising that while specialists will understand the capabilities of their simulation tools, and designers know what they are trying to achieve from buildings for their clients, designer's questions in building terms will always require to be translated into simulation objectives. During the early stages of design, it is common to construct geometrically simple models, which often contain simplified representations of building occupancy, material properties and internal heat gains. Such models are useful in analysing the general form and orientation of the building and, if carefully contrived, can be evolved as the design progresses.

A successful outcome will hinge on the combined strength of the team and the suitability of the appraisal program. Design team members can often identify potential problems by conducting early design checks using simple and traditional design tools to evaluate orientation options and inform issues such as site layout. This helps to build confidence in the overall approach and assists in determining which questions remain unanswered or which issues appear to be critical.

3.5.3 Translating design questions to simulation tasks

Of fundamental importance is to be aware of the appropriateness of the tool(s) selected in relation to the problem(s) being investigated. This was a key issue for the research to date, which relied heavily on the in-house researcher's skills to match the most appropriate specialist, possessing the best tools to address the design issues posed, with the design team involved. This required skills beyond the practicalities of simulation, in that, communication of design ideas and simulation capabilities between designers from different backgrounds can lead to confusion. In this respect the in-house researcher acted in part as an advisor, in part as an adjudicator, but first and foremost as a conduit through which the necessary dialogue could take place, in order that design questions be translated into terms that could be addressed by simulation.

Table 3.1 offers examples of how design questions might be translated to specific simulation tasks.

Table 3.1

Translating Design Questions to Modelling Tasks (after table 5.1 AM11, (CIBSE 1998)).

Design question	**Modelling task**
Does this building require air conditioning?	Ascertain by simulating a naturally ventilated building, what will be the peak summertime temperatures and the frequency of occurrence.
If borderline, what measures might eliminate the need?	Explore key design parameters such as floor plate depth, ceiling height, thermal mass, window design, physical shading opportunities.
If so, which air conditioning system will be the most energy efficient?	Compare the degree of temperature and humidity control possible for various system configurations and evaluate the required cooling capacity and associated system energy consumption.
How can daylight penetration be maximised and glare sources eliminated?	Evaluate and compare daylight factors and glare indices for a range of glazing options and a variety of shading devices - individually and in combinations.
Will displacement ventilation be able to cope with the high levels of internal gain?	Explore the appropriateness of the anticipated internal gains. Once agreed, determine the occupied zone comfort levels for a range of loadings and supply air conditions.

Note: Modelling tasks identify issues and/or performance indicators, ***not*** *the specific appropriateness of the programs to be used or the nature of the required model to address such issues.*

3.5.4 Common procedures for undertaking simulations

On agreement of objectives, it is important to develop a clear simulation procedure before the work begins. This is necessary for quality assurance purposes in order that: other design team members can be fully involved in the process; that they are able to monitor the progress of the simulation work at any point; and to allow the development of a consistent approach across their organisation to addressing similar studies in future.

A key task is the identification of the programs required to answer the questions asked and the level of resolution required to achieve the objectives, leading to production of the information needed to create the required models and to sequence of assessments necessary to evaluate building performance. The benefit of previous experience may assist design team members to develop initial hypotheses about the design. This can be valuable in terms of program selection and to help decide the number and type of models to be created. The degree of detail should be appropriate to the design questions to be answered. For example, adopting an approach to reference model development based on known best practice for day lighting and natural ventilation in terms of floor plate depth, ceiling height and glazing distribution, would automatically reduce the number of iterations necessary before exploring more innovative aspects of the design. Such insights, together with traditional rules of thumb and manual calculations, can be of assistance in creating a general understanding of how the building is likely to behave. However, buildings do not always behave as expected, and a degree of flexibility in terms of dealing with the unexpected is required.

In the case of the research, the benefit of over 10 years of experience and around 1500 enquiries on which to draw proved highly beneficial in drawing to the attention of design teams and specialists the benefits of hindsight on numerous occasions. For example: an unexplained energy loss that was identified as being attributable to a previous refurbishment, which had damaged the integrity of the air tightness in a system-built local authority office block; unexplained 'dampness' in a dwelling attributable to mortar on wall ties; and severe afternoon overheating in a south facing school resulting from the release of heat late in the afternoon, caused inadvertently by the use of solar absorbing glazing film to alleviate glare.

Figure 3.2 sets out a typical simulation procedure. This will vary from project to project depending on the number of issues to be addressed, at what level of detail and the complexity of the building in question. It should be noted that the direction of the study may change, depending on the simulation outcomes.

The remainder of this section deals with general considerations regarding model development, and, in particular, the issues of problem *abstraction*, development of a *reference model*, choice of *climate*, and model *zoning*.

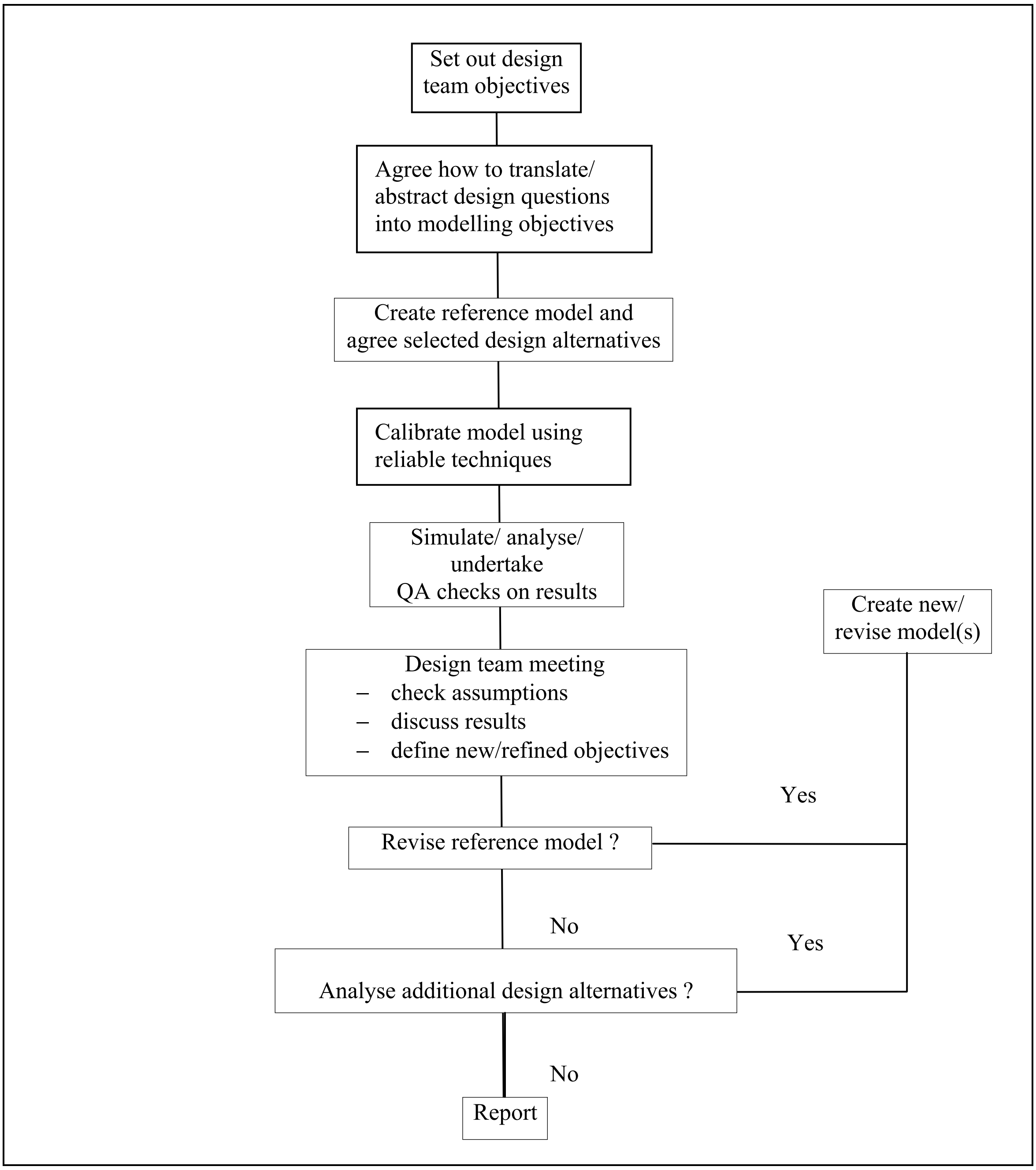

Figure 3.2 Typical simulation structure (after figure 5.1 AM11,1998)

Abstraction

Observations in the field over the previous eleven years highlighted the recurring theme of the need to make an abstraction from a ‘real’ building design to how it might best be represented in a model for simulation. Abstraction is an art that can either be learned by experience or left to the skills of a specialist. If applying a tool in practice without expert support, the modeller needs to be aware of the potential impact of any assumptions made in addition to those inherent in the program being used. The aim should be to keep the model as simple as possible while avoiding the errors that can result from over simplification.

For example, if investigating comfort in a large volume space such as an ice-rink or swimming pool, what appears to be a single zone actually has a wide variety of interactions taking place that will greatly affect the comfort of occupants, from the ice/water users to spectators with varying clothing levels and levels of activity, not to mention the rates of evaporation caused by air movement and temperature differentials. This may seem obvious, but just how many zones need to be considered? Is a part macro-/ part micro- analysis required? And if the ice rink is replaced with a factory shed, does this require the same level of scrutiny? This will depend on many factors from materials, to proposed energy systems, and so on. Alternatively, a common mistake is to create an overly complex model, and as the model grows more complex, the potential for input errors and the cost of quality assurance increases. Resolution of these dilemmas is a non-trivial task, and relies as much on the understanding of how buildings work as it does on simulation skills. At this point in time, although such a methodology could in theory be applied by designers, it was recognised that few were yet ready to take such a step unaided.

Within the earlier phases of the research, specialists were employed to undertake this work with the design team learning by observing the process. Assuming a professional level of understanding of how buildings work, and the associated regulatory systems that apply, a simplified approach was developed to guide the novice user:

– create a model based on simplified geometry;
– use known or typical/ appropriate default constructions;
– use known or estimated internal gains (consider how these will vary over time);
– use regulation compliant ventilation rates;
– opt for 'ideal' internal environmental set-point temperatures and humidities.

Post simulation, the results can then be studied to determine what has the greatest impact on performance. In order to test this, a sensitivity analysis, such as changing one parameter and observing the effect on the predicted performance in order to explore what is 'driving' the conditions within the building: e.g. the ventilation rate might be doubled; or the occupancy level varied throughout the day. It is important not to cause confusion by changing too many things at once, as this can result in multiple, incoherent results whereby it is impossible to decipher what is actually going on and this usually reveals little – patience and rigour are crucial in simulation - better results are usually obtained by changing one, or a few, input parameters and re-simulating. Understanding the dominant influences leads to improved design robustness. It is also advisable that the results from these sensitivity analysis simulations be archived, and the effects on performance catalogued. However, changing only one parameter at a time can unduly prolong the process, over time as confidence grows, simulators build up a level of expertise that supports decision making to the extent that the driving influence in specific project types is (to an extent) recognisable, allowing a more radical approach. For example, if a building is destined to have a double skin façade, there is no point in creating a base case model based on a conventional approach, whereas if the design team/client are undecided as to approach, the conventional approach may be an appropriate starting point. However, generally, in the early stages of expanding the design team's modelling expertise, a more cautious approach is recommended without being over-constrained. Moreover:

- it is important to ensure that the simulation tool incorporates the functionality required for the anticipated range of applications; and
- as the level of detail will affect accuracy - the user must judge, whether or not all of the variables that are likely to have a significant impact on the performance issue in question are included in the simulation model.

Reference model

It is likely that several design options will be under consideration. A *reference*, or base case design is therefore required against which these alternatives can be compared:

- for a new-build project, the reference is normally the initial design intent. Generally, novel or unusual features would be excluded from the reference model, in that design alternatives can then be incorporated within model variations and the predicted performance of these compared with the reference as the design evolves;

– for refurbishment projects, the reference case is normally the existing building. If available, the actual building performance predictions can be compared with the simulated building as a rough check on accuracy of the model.

What to and what not to model, present dilemmas for both novice users and for specialists acting on their behalf. For example, it was observed that even if a non-expert designer could be reassured that the appropriate model may not 'look like' the building, the client often expected to see a computer model that accurately represents his or her expectation, confusing *representation* with *visualisation*. In fact, relying on models that look like the building as perceived by the client and design team, can mask common mistakes – for example are the volume and size correct? In 1990 it was not unheard of for a building to be measured using imperial units and input to the model as metres, resulting in a building that was perfectly in proportion – but which was around thirty times the volume it should have been. It is important to check all such details every time a model is created and to remember that, we can be easily seduced by what appears to be right – so not only is it often appropriate to model only a part of the building, (e.g. where many rooms have similar design features and functions – such as a hotel or office), but also, such a model is more likely to be scrutinised more closely, reducing the risk of data input error. This issue is explored further in this section (see ***Computational parameters*** and ***Risk and uncertainty***).

Similarly, for occupancy and other internal gains, rather than attempting to define actual schedules it is often adequate at the early stages to estimate the occupant density and hours of occupation and to match office equipment gains, lighting loads and heating set-points, etc., with this. The characteristics of such scenario-based modelling are that (a) it is representative rather than accurate, (b) it covers a range of values of key parameters, and (c) several parameters may be changed together to maintain internal consistency.

In practice, in early research observations, users were very concerned that the input data was collated as accurately as possible – despite the fact that they had no control over what would actually happen in practice. In one project, by the date of occupation, the client had increased the number of occupants in a daylit office with mixed mode, displacement ventilation, by 25%. This had a knock-on effect on everything from internal heat gains to furniture layouts (and subsequently on floor mounted diffusers, daylight distribution and comfort). In the past, in fully mechanically treated spaces, such a change could have been accommodated more readily.

In the case of artificial and day lighting studies, in order to explore the impacts of surface colour and form and shadows caused by furniture and fixtures, individual spaces tend to be assessed in greater detail than for thermal models, so if undertaking both thermal and lighting analyses within a single program or using the same building model, it may be appropriate to create a more detailed model than is necessary for the thermal analysis alone, as this will facilitate the features necessary for a follow-on lighting analysis, e.g. fenestration details, shading devices and internal fittings, etc., as shown in Figure 3.3. Site context is clearly important in both cases, in terms of the impact of surrounding buildings, shading from foliage, etc.

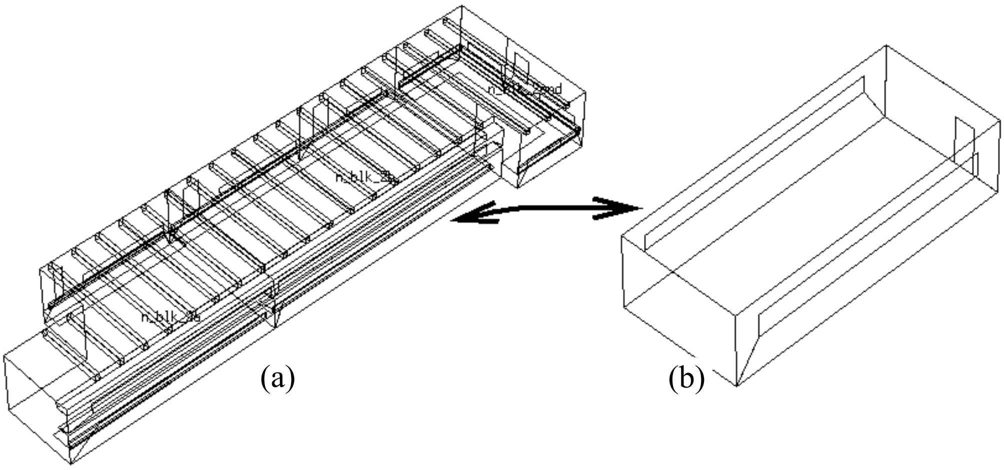

Figure 3.3 Modelling at an appropriate level of detail - lighting (a) and thermal analysis (b).
(after figure 5.2 AM11,1998)

Other common mistakes in preparation of the reference model include:

- forgetting to orientate the building to site co-ordinates;
- attempting to increase realism in images, which in turn increases simulation time significantly without adding to the relevant information obtained;
- omitting important site features such as adjacent buildings and vegetation.

Climate

The selection of climate sequences for simulation purposes will depend on the simulation objective, e.g.:

a) short sequences (e.g. one week) selected to represent average conditions (in terms of solar radiation, temperature and wind for example) for particular seasons;

b) design days selected for predictions of peak loads and temperatures; or

c) annual sequences for overall energy consumption estimation.

In the case of short climate sequences, the user should be aware that the climate during the days immediately prior to the period being simulated will generate the starting conditions for the building, and to take this into account in relation to the issue being investigated. For example, do not select a weekend for a building for which a Monday – Friday occupancy and heating regime have been set up. The appropriate sequences should be selected to ensure peak values occur on the required day of the week.

During the late 1980s and the 1990s, the research identified, that if using simulation rather than a simplified calculation tool, designers became very climate conscious, in that, they often queried – *how accurate is the climate? is there a source of local weather data? can we set up a weather station?* On the basis that - *our weather is very site specific here… it is very different only three miles away… UK weather is inappropriate in this location,* and so on. In fact, discussions about climate and weather took up an inordinate amount of time, compared with other, potentially more influential factors such as how to take into account the potential of fabric mass to mediate temperature swings; the difficulties associated with accurate plant simulation; and how to model occupant behaviour. Much time was spent on explaining the benefits of using averaged, complete datasets for typical studies, and looking at 'future proofing' using *what if* scenarios for example: if trying to avoid air-conditioning, rather than attempting to use monitored data, which would at worst include only some of the data required and at best is unlikely to be typical of weather or climate in the area. That is not to say that there is never a reason to monitor weather, but it is not usually the best way of capturing data for simulation purposes.

Whatever climate sequence is chosen, it is important that this is noted for future reference in order that the severity of the conditions (e.g. typical or extreme) is recorded and remains accessible.

Zoning

As suggested above, the temptation to create a zone corresponding to every room should be resisted. However, it can be difficult to convince a client that such a model accurately represents the building in question. This was more of a problem historically than is the case now, as the advent of easy to use CAD tools makes it possible to build models rapidly, even if only for the purpose of visualisation.

In the case of thermal models, spaces in a building can be grouped together into one zone if, for example:

– they are likely to perform similarly without environmental controls;
– they have similar heating and cooling equipment and set-points;
– internal gains from occupants, lighting and equipment are similar; and
– solar gains are similar.

All of the above might apply in the case of typical offices or classrooms in the same orientation or heating zone for example. If the partitions separating spaces grouped in this manner have significant thermal mass, this should be included within the modelled zone, if not, it may be possible to exclude them.

On the other hand, spaces should be split into more than one zone if, for example:

– variations in environmental conditions within the space are of interest – such as the case of the swimming pool, where humidity might be an issue;
– there is likely to be temperature stratification – e.g. an ice rink, theatre or a high bay factory; and
– solar or internal gains differ significantly throughout the space and mixing of the air is limited – for example a north-south facing school with high solar exposure or an office with displacement ventilation.

During the early observational research, clients and non-specialist designers often confused computing power with ability to generate accurate geometry. This resulted in some cases in the need to develop models that looked right, even when a 'box' model with a representative percentage of glazing on each façade would have been appropriate for the task in hand – this perception persisted until the novelty of computer graphics wore off and also as design teams began to undertake work themselves as the 1990s ended. In the meantime, the developed methodology clarified when and how it was appropriate to group spaces into one zone and when it was not, but whether or not designers working without the aid of a specialist were confident in adopting the suggested approach was unclear at this stage.

Shading and internal solar distribution

Estimating peak summertime temperatures and cooling loads in a space is an issue that can be addressed by laborious manual calculations or by simplified tools that employ the same method (CIBSE A8 Calcs). However, assessing the potential impact of solar gain and shading effects on diurnal internal temperatures and comfort requires a more accurate assessment method. In most cases, other than on open, rural sites, comfort, cooling loads, internal temperatures and lighting are all affected by the adjacent buildings and 'self shading' from the building under consideration. This issue can be addressed by many tools to a greater or lesser extent, and whereas simplified tools can provide the possibility of viewing the building model from various sun positions, in order to determine the importance of shading, detailed analysis tools can simulate the probable impact of solar gains and the need for shading or an alternative approach to addressing heat gain from the sun.

The simple approach of 'attaching' overhangs to facades was often used in early studies to demonstrate the difficulty in shading facades that do not face directly south, and the need for vertical shading to deal with east and west orientations. This does present the risk of heat being trapped beneath simplified solid shading device, which can impact on ventilation strategies and predicted overheating risks. Also, for highly glazed spaces or for detailed studies, it may be necessary to undertake an analysis of the solar reflectance, absorptance and transmittance between the opaque and transparent modelled surfaces of the building in question.

On the BA Headquarters project at Heathrow (figure 4), a narrow 'street' atrium, connects finger-like offices, which it was anticipated would be self-shaded, thus reducing the need for air conditioning all year round and allowing natural ventilation at least some of the time. In order that daylight was not compromised, the 'fingers' were light in colour with pools of water between them in order to reflect light into the interior. Simulation resulted in significant plant cost savings for an overall study outlay of around £20,000.

Figure 3.4 – BA Headquarters Heathrow (image courtesy of Buro Happold)
http://www.burohappold.com/BH/PRJ_BLD_british_airways_headquarters.aspx

In undertaking such a study, it is important to take into account as many of the relevant factors as possible through sensitivity analysis. For example, if investigating self-shading and reflected sunlight and daylight, it is also necessary to take into account factors such as site exposure and topographic effects: surrounding hills may channel wind on to the site and/or cut off afternoon solar access. Site photographs, ordinance survey maps and on-line maps can assist in pinpointing issues that should be taken into account.

Ventilation and infiltration

Designers are familiar with the application of the recommended infiltration and ventilation rates used in traditional manual calculations building compliance standards. Simulation offers the opportunity to also test what might happen in practice as a result of measured, designed-in or accidental air flow paths, from idealised air change rates, through air leakage networks, to detailed studies of air movement by computational fluid dynamic (CFD) programs. Typically, if simulating a building at the early design stages, in order to test the model against probable behaviour (based on the design team's experience) modelling would begin with idealised representations of possible flow regimes (i.e. specified air change rates), moving to the more explicit network and CFD representations where pressure or buoyancy-driven air flows dominate performance.

The value of design team experience should not be under estimated. Based on early experiences in the research work, clients and design teams often requested a CFD study without understanding the design issues that required to be addressed. This was an anomaly in an environment where designers were not yet comfortable with what simulation could and could not address. Often they appeared to be seduced by the notion of using CFD, perhaps at that time because the associated graphics exceeded the quality of that available from a wire-line thermal model. Somehow there was a value attached to the notion of CFD, a sense that a CFD image would impress the client or justify spending money on a simulation. With the advent of vastly improved computer graphics in modelling generally, the lure of CFD has diminished, but throughout the period of the research, observation indicated that until the end of the 1990s there remained a tendency to value appearance over quality of output.

In summary, for comparative studies or early design stage estimates of energy consumption, a simplified fixed ventilation/ infiltration rate will generally be adequate, especially in the hands of, or advised by experienced designers. For more detailed questions relating to how air might move or for natural ventilation studies, a more detailed approach, exploring bulk air movement throughout the building by setting up an air flow network based on openings and leakage paths in and around the building may be required. For detailed air movement studies in a single space, such as for removal of contaminants from clean rooms, the use of CFD software would be required. However in order to improve the accuracy of such a study, a thermal simulation or physical test will be required to ascertain boundary conditions such as surface temperatures to improve the accuracy of the study – in other words, CFD is likely to be at its most useful towards the later stages of a simulation analysis, not as a starting point. To be accurate, CFD simulation requires detailed inputs, down to location and concentration of contaminants and furniture details. Even although an iterative approach is necessary and choice of gridding and surface temperatures can significantly affect outputs, it is important to be pragmatic and not to accept results at face value.

Plant and control

Simulation programs offer up a wide variety of levels of detail for building systems, plant and control, ranging from idealised systems with instantaneous response and fixed set-points to detailed representations with real control action characteristics. In the case of early stage or comparative studies it is generally adequate to adopt an idealised approach, progressing only to more detailed models after the building-side design parameters have been fixed. For example, an ideal convective heating system with ideal control is adequate to answer questions on thermal comfort where it is known that the heating system will be able to provide a certain maximum amount of heat. However, the energy consumption figures should be treated with caution with idealised systems and control, as factors such as boiler efficiency and thermostat moderation are not considered.

Within the early days of the research, ideal control was employed for most evaluations as the development of more accurate control algorithms within programs was in its infancy, but as design questions began to change - e.g. from general energy consumption, and maximum summertime temperatures to issues of comfort control, mixed mode ventilation and avoidance of air conditioning, the need for a more accurate approach was required and detailed representations began to emerge. And, as the use of more detailed control regimes emerged, (for example for mixed-mode ventilation systems where 'free' cooling would be used when the outside temperature was lower than the internal, switching to comfort cooling as outside temperatures rose), unexpected anomalies began to emerge. Examples of this include: internal temperatures over-shooting and spiking, and systems appearing to have huge peak plant requirements as they struggled to reach set-points within an hour of plant being switched on. Such instances indicate a failure to match the simulation time step to the response of the system or control component. Although obvious to simulation program designers, this caused some initial confusion – even for simulation experts. This situation was easily resolved by a detailed examination of the results, but it highlights the importance of undertaking appropriate tests to ensure that system performance is well understood.

Occupancy and small power

Representing occupancy and small power heat gains, can be problematic as these tend to be stochastic and the peak values traditionally used in steady state methods will overestimate usage. For assessments that look at performance over time, load profiles should be used which include both peak and typical values. The actual casual gain profile is likely to be an issue only in detailed assessments. In such cases, it is necessary to ensure that the correct total gains are accounted for and that a schedule is developed that seems logical and can be agreed by all stakeholders in the process.

The impact of occupant behaviour on thermal performance has always been a difficult area to model. For example, people shut down radiator valves and forget to open them again for the next day, they open windows before switching off heating; they leave windows open on cold days, lights and equipment on overnight, and so on. Although simulation can be used to investigate such effects, it is usually assumed in simulation that buildings are operated sensibly.

During the period of study, it was generally accepted that it was almost impossible to account for the behaviour of occupants, and users of the service were in the main content to accept this – given that hypotheses could be tested by including best and worst case scenarios.

The impact of occupant behaviour on performance is an ongoing area of research, and steps are now being taken to build-in stochastic behaviours to the simulation of casual gains (Rijal *et al* 2008).

It should be noted that over the period of the work, the impact of IT loads varied dramatically, at the beginning in the late 1980s, IT loads were insignificant as few people used computers on a daily basis. The heat gains from early electronic equipment were relatively high compared with the situation at the time of writing (around 200 – 300W/pc compared with around 30W now) and so as computer use grew, office equipment gains began to drive the need for air conditioning – to a point where in the mid 1990s in typical offices, everyone had a pc and possibly a printer on their desk.

However, by the mid 1990s, equipment was becoming more efficient with greatly reduced associated heat gains and in 1994 BRECSU published a guide to energy conservation in offices (ECON 35 Energy efficiency in offices – small power loads) to assist designers struggling to pinpoint the actual gains from equipment. This issue highlighted the need to constantly review what we regard as *normal* with regard to assumptions made in the design of buildings, an issue that should be built-in to any simulation procedures in design practice.

These variations also applied to other types of small power loads, from lighting to lifts and escalators. The introduction of mixed mode ventilation brought extract systems that pulled air over the lighting system, thus removing the heat gain at source. Such changes in technology and approach should always be taken into account. And, just as it is necessary to keep up with changes in technology, work patterns and occupancy patterns are no longer as fixed as they once were – it is important to work closely with clients on such issues, as occupancy assumptions can have a significant impact on performance predictions.

Thermal bridges

While the presence of thermal bridges within a building will not necessarily affect energy consumption or comfort conditions, depending on the severity of the problem, there can be resultant health effects (e.g. due to spores and mould growth); spot comfort issues due to cold radiation and deterioration in fabric performance (e.g. due to interstitial condensation) over time. However, the impacts are unlikely to be significant unless the thermal bridges are close to the internal surfaces or there are major structural elements linking the internal to external environment. In severe cases, or for detailed interstitial condensation analysis, it may be necessary to use a 2-D or 3-D steady state or dynamic thermal conduction program to analyse performance. In other cases, for example a timber studded wall, the constructional materials should be based on a proportional area method, as for steady state calculations described in the Scottish Building Standards (SBS 2009). It may also be appropriate to combine site survey techniques such as air tightness or thermographic studies with simulation in order to pinpoint the source of the problem.

The research included a significant number of diagnostic studies, from investigating the cause of damp patches and mould growth in a private house using a combination of simulation and on-site invasive testing, through studies to alleviate of mould growth in local authority dwellings by introducing 'solar ventilation' via solar energy capture from behind roof slates, to an analysis of the behaviour of leadwork repairs on a major conservation project in Edinburgh's New Town. These studies pushed the capabilities of the available simulation tools to the limit of their (then) capabilities, and in one case influenced the development of a significant research project (Clarke *et al* 1999), predicting the conditions in which certain types of mould will grow and alleviation techniques to reduce the associated health risks.

Because steady state and early simulation tools were not able to undertake detailed analysis of thermal bridging this area was, to an extent neglected in the past, but as insulation levels improve, the potential impact of cold bridging is becoming more significant, and should not be ignored. Further, simulation can now be used in a diagnostic sense to alleviate the resultant problems.

Computational parameters

Setting the boundary conditions for a computational analysis is a critical issue in simulation. Generally, programs will make initial assumptions on temperatures, and then use *preconditioning periods* in order to allow conditions to arrive at a realistic state before any assessments begin. The ideal preconditioning period is normally flagged by the program based on fabric/ building response times, and the user can then adopt or reject the recommendation - although checks can be carried out based on different start-up periods to ensure that the predictions are unaffected by the assumed starting conditions. The recommended start-up period can also assist by highlighting anomalies in fabric or other parameter selections – e.g. in the case of simulating a heavyweight/ slow response building one might expect a long preconditioning period in order that the fabric is in a settled condition before the process begins.

The setting of boundaries was often a point of discussion with the appointed specialists and users in the early days of simulating the impact of fabric mass on mitigation of overheating in buildings that relied on passive heating and cooling. Over time it became an integral consideration in displacement ventilation studies where the extract was drawn through a heavyweight ceiling. Often programs would indicate extremely long start-up periods due to the sheer mass of fabric and knowing when to compromise and how to reduce preconditioning requirements is an art. Specialists demonstrated to users a number of ways around the problem – e.g. firstly setting a benchmark by adopting the recommendation as a test case and then re-simulating with a reduced period or, for programs based on finite differences and finite volumes, testing the impact of dividing a thick wall into an equivalent number of slimmer elements: in some cases it is advisable to subdivide layers greater than 100mm in thickness.

Not only does this assist by building an understanding of what is and is not appropriate, it also builds confidence in recognising what one should expect. Some programs require the user to specify initial conditions: again the user can check the influence of any assumptions in similar ways to those described above.

For thermal simulation, the most appropriate time-steps will also depend on fabric response times and on the method of solution. In some programs, the program calculates the time-steps, while others require the user to make the appropriate decisions. Again, experience of working alongside an expert would allow the user to gain the appropriate experience by undertaking sensitivity studies at different time steps. As a general rule, hourly time steps are suitable for general energy consumption studies and 15 to 30 minute time steps if examining building response. However, for detailed studies of plant and control systems, simulation time steps of the order of one minute may be required to ensure realistic control.

Another study appeared to provide meaningful results in terms of annual energy prediction, but on closer inspection, the internal conditions indicated poor comfort levels. It was discovered that the floor had been input with the outer layer of concrete on the inside and the floor finish outside. Not only would this affect comfort levels, it also affects external heat transfer coefficient, replacing one associated with an internal surface with that associated with a surface in contact with the ground. Not all programs require that information is input using the same conventions, and this once again raises the importance of checking that the model displays the expected dynamic behaviour.

Risk and uncertainty

What are the risks in adopting a computational approach to the design process? Particularly on projects of significant scale or importance, where incorrect or ill-informed decision-making might result in major financial consequences, it is important that the risks are fully assessed and the uncertainties properly accounted for.

Despite a great deal of work in this area recently (Macdonald *et al* 2004), at the time of the research, other than flagging up *unusual* or *unexpected* inputs, in the main, simulation programs gave no indication of uncertainty in predictions and this was left to the user to assess. Some assessment of uncertainty (and therefore risk) can be derived from past experience or by undertaking sensitivity studies of the effect of important model assumptions. Although simulation can identify optimal performance, the user should check that slight changes in model assumptions do not result in unacceptable impact on performance. The issue of not knowing what to expect combined with the risk of not recognising anomalies in output were key factors in a) the setting up of a design advice service, and b) the continued support for the service by users, who would rather that these risks lay elsewhere. This relates back to the issue of PII cover, in that there was no precedent for carrying the risk of the building performing differently from the predictions. The whole issue was compounded by the fact that designers were becoming increasingly interested in the use of simulation for the evaluation of passive features in buildings, thus increasing the risk to designers who specified smaller plant or no plant at all. This also presented a significant barrier to the in-house use of simulation.

In essence, there are three types of uncertainty: that associated with the unpredictability of the future (weather, occupancy, operation, levels of maintenance etc.); that associated with approximations within the mathematical models and their implementation, and that due to imperfect knowledge of data input values (e.g. for material properties). The effects of uncertainties can be determined by sensitivity studies. While no predictions are without uncertainty, the appropriate application of simulation should lead to more confidence in the design than simplified assessment methods.

3.5.5 Interpretation and presentation of results and reporting

Translation of simulation analysis results into information that can usefully inform the design process is a non-trivial activity. Outputs will be program-specific and this further complicates the task of transforming the information into a format that enables decision-making. It is recommended that the ability of software to produce the required information at the necessary level of detail and then to either present or export this to another application for post-processing should be one of the key criteria used in selecting a tool. This issue is further discussed in section 3.4.3 and in chapters 4 and 5.

It is also important that the results are unambiguous and transparent to specialists and a variety of design team members who may require information at different levels of detail. For example, this might range from a straightforward 'the building does not significantly overheat' to a comprehensive breakdown of time-varying comfort conditions in various spaces in the building. One of the benefits of computer-based assessments is the richness of information that can result from one set of predictions. On the other hand, experience showed that the degree of rigour with which the simulation methodology was applied, was critical to delivery of meaningful results. For example, lack of attention to detail in large volume spaces could result in inadequate zoning which if compounded by an over-simplification of the fabric and controls strategy could suggest that the 'building does not significantly overheat' based on average air temperatures, say, but that this could belie temperature stratification, inappropriate environmental temperatures (e.g. due to hot or cold radiation from surfaces), and variations in temperature and comfort not picked up because of an inappropriate approach to selection of simulation time steps.

The following should be considered on a project by project basis:

- the need for an iterative process with the client to ascertain exactly what are the key issues;
- to avoid confusion, report only on the relevant data, but be mindful of the fact that this is part of a bigger picture e.g. the peak summertime temperatures in a school may occur during the holiday period;
- in the case of several design variants, it is important that the reference case against which parameter variations have been made is clearly defined;

- quantify where possible: e.g. number of hours overheating, lux level contours for standard overcast sky;
- explain results: e.g. if a model change increases energy consumption, explain the causes for the increase.

If fully taken onboard, the latter two points will go a long way to bringing the required level of rigour to the process, and will assist the specialist and practitioner to identify whether or not results make sense.

Reporting

For clarity, in terms of presenting the results in a manner useful to the eventual decision-maker, a report should have:

- a statement of study objectives;
- a summary of the main findings;
- brief details of relevant capabilities of program used (with version number, etc.);
- a description of the model: including a description of how the model was formed and the principle operational characteristics (with reference to details in Appendices if appropriate);
- assumptions made in the model and results of sensitivity analyses where appropriate;
- a clear description of design variations tested and changes made;
- graphical and tabular results (refer to examples in case studies);
- conclusions against stated objectives; and
- outline pros and cons of design variations.

The following section illustrates the application of the above methodology. This case study was selected in order to illustrate the application of the methodology in practice on a major project undertaken within the final stage of this phase of the research. It is one of a number of case studies originally written up for the CIBSE Applications Manual – AM11 Building energy and environmental modelling (CIBSE 1998).

3.5.6 Case study – Victoria Quay

The simulation methodology described above emanated from years of observation of the use of simulation by specialists on real building projects. This case study is chosen to illustrate the key points raised in the previous section, as observed and recorded in 1998, towards the end of the third stage of this phase of the research. It was not selected on the merits of the specific building itself, and so an in-depth description of the building is not provided. Rather, it was chosen as illustrative of the ways in which integrated simulation had gradually been adopted and integrated into the design process, albeit in a *hands off* way remaining firmly a specialist activity. It is intended to provide an insight into why, and at what stage the decision to simulate building was taken, what was the impact on the design process and how simulation informed the final design.

Victoria Quay is located at a latitude of 55.4^{o} North in the Leith Dock area of Edinburgh, on the east coast of Scotland. The site is flat, open and subjected to very little overshadowing. The $35{,}000m^2$, four-storey building was designed by RMJM (Scotland) to house 1,500 personnel of the Scottish Government.

An attempt has been made to cover the diversity and depth of questions posed by the designers. In addition to detailed design requirements relating to complex issues, information has been gathered and integrated from other studies relating to typical design issues such as performance of building services equipment. The case study covers both the highly serviced nature of the building and also more passive approaches to environmental control.

This case study represents different application problems and scales in a prestige office development, and demonstrates the application of the methodology outlined in *3.5.1 – 3.5.4* in a study conducted over three phases and various levels of detail and covering several design issues ranging from the performance of the building in relation to form and fabric generally, to the impact on energy performance of enhanced daylighting and the use of mixed-mode mechanical and natural ventilation in particular. Given the scale of the building and the modular nature of the design, the study focuses on the selection of 'typical' zones to illustrate general trends, in-depth materials and comfort studies, and then extrapolation to predict overall energy performance.

Fig 3.5: Victoria Quay.

The case study elaborates the following elements:

- an outline description of the *Design Team Objectives* and the issues of interest to the designers at the outset;
- identification of *Design Questions* and translation to *Simulation Objectives;*
- a description of the *Reference Model* and *Input Data Requirements* in terms of development of-the model;
- *Interpretation of the Results* obtained;
- a description of the final design and how the simulation exercise influenced this;
- a brief discussion of other issues, which could have been investigated by simulation but were not included in the study.

It does not attempt an exhaustive coverage of issues, rather it highlights points which may help in the selection and use of assessment tools on any such project.

Performance issues covered in the case study are:

- *building form*: use of open courtyards and atria for natural ventilation and daylighting;
- *fenestration and fabric*: natural ventilation, free cooling, thermal mass and mixed mode ventilation;
- *façade*: shading design; and
- *energy*: peak heating loads and energy consumption.

Design team objectives and approach

The primary aim of the design team was to construct a low energy building that would avoid the need for air conditioning. The intention was to achieve this by making use of the thermal mass of the proposed heavyweight structure to absorb solar and internal heat gains in order to reduce diurnal swings in temperature.

Using recognised design principles in relation to plan form, glazing distribution and thermal mass, and drawing on experience gained from an earlier RMJM building for the National Farmers' Union (NFU) in Stratford Upon Avon, the designers had produced a concept design for a naturally ventilated building. In order to proceed with confidence, the team recognised the need for a reliable assessment of the predicted performance of the building, and employed specialists to assist with the analysis of the project. The concept design was discussed with the design team, the specialist simulation experts and the in-house researcher who acted as an advisor throughout the project. Issues studied included the development of the building form and the designers' aims. At this point, the key design questions were formalised.

The team explored the potential to use the building's thermal mass to avoid air conditioning and expressed a preference to exploit daylight and natural ventilation by punctuating the building with atria and courtyards to create narrow plan forms. Another area of interest was the use of a 'mixed mode' ventilation system whereby the building would rely on natural ventilation in summer, but would be mechanically ventilated in winter to optimise loads and energy consumption. Although well used and understood at the time of writing, in 1997, mixed-mode ventilation was considered an innovative approach, and few benchmarks existed against which the design could be compared.
Other design issues raised in the early discussions, included:

- the possible requirement for 'night purge' ventilation overnight to address residual heat storage in the fabric overnight by pre-cooling the structure; and
- glazing specifications, surface finishes and how to provide protection from glare and overheating were also raised as issues that should be explored.

Identification of design questions

Following discussions between the design team and modellers, a three-phase approach was planned. Initial studies would focus on the optimisation of fabric mass and building form, and in particular a comparison of the configuration of the central open spaces and atria in terms of thermal and natural ventilation performance.

Phase 1: *Design principles – can the building deliver the design objectives?*

- Will natural ventilation alone provide adequate fresh air and prevent overheating or is some additional mechanical ventilation required?
- What are the benefits of features such as atria and courtyards in terms of thermal comfort, ventilation performance and energy saving?
- What, and when, are the peak building and plant loads and what are the main contributing factors?

Phase 2: *Design refinement*

- What advice can be given on the detailed design of shading devices and selection of glazing systems to reduce the overheating risk?
- What ceiling design would ensure good thermal contact between the air and the structural mass?

- What would be the impact on comfort and daylight distribution of introducing cellular offices around the periphery of the building?

In practice some of these questions arose as a result of the findings of the Phase 1 study.

Phase 3: *Quantification of the performance of the final design*

- Is this a low energy building?

It was decided to address this question only after the form, fabric and system design issues had been optimised.

Simulation objectives: Phase 1

Before the simulation exercise could commence, agreement had to be reached on what was an 'acceptable' summertime internal temperature, and also, on selection of climate, materials specification, zoning, and fenestration strategy in relation to natural ventilation. Given the fact that the team was nervous of the fact that the proposed approach was novel and offered little scope for error compared with adopting a uniform air-conditioned approach, this proved to be a non-trivial activity – and included discussions on whether or not there was a need to set up an onsite weather station. The team was persuaded that an onsite weather station would provide little benefit in terms of recording typical site conditions, and it was agreed to adopt the CIBSE recommendation of a summertime maximum dry resultant temperature of 26^{o}C, which should not be exceeded for more than 10% of the working day in summer (around 100 hours).

To address the identified design questions the simulation team had to:

- predict peak summertime temperatures assuming natural ventilation and compare these with the performance target set by the design team.
- compare the thermal performance (thermal comfort, overheating risk, energy consumption) of the building with three design variants of the central space (atrium, open courtyard and atrium with north light only) under winter and summer design conditions.

Reference model & project database

In order to allow performance comparisons, a reference model was created. From this reference design, other variants were created during the course of the study to investigate the different design options.

The reference model was developed based on the outline stage building design as proposed by the design team at that point in time. Essentially this comprised a concrete structure, naturally ventilated in summer with an atrium to aid the cross flow of air. In winter, mechanical ventilation would be used to eliminate the need to open windows, thus reducing excessive infiltration losses. Detailed information relating to construction materials, occupancy details and equipment loads were provided by the design team. Information regarding materials specifications; internal heat gains from people, lighting and equipment; and the proportional split between sensible and latent/ radiative and convective heat gains were identified as being critical to the prediction of internal temperatures and the optimisation of the design. However, the accuracy of such information depends on the information supplied by the building client, and this may vary over time. Simulators therefore often have to explore a number of 'what if' scenarios based on past experiences (e.g. will a 10% increase or decrease in staff or equipment loads adversely affect performance?).

Climate data

The site is not typical of an urban location and is almost coastal in nature. The design team expressed particular concerns about the local wind conditions in relation to prediction of the building's performance in summer using natural ventilation only. The design team and the consultants discussed the choice of weather data at length. The options were to use a standard UK weather set, compose a hybrid set which incorporated site measurements into a standard set or to find data for a similar site (east coast of Scotland, sea level, near mouth of river, open site).

The design team did not consider the wind patterns in the 'standard' UK weather data set to be representative and suggested approaching the Meteorological Office and the port authorities for local data; the simulation specialists expressed concern about the inconsistencies which might be introduced in a hybrid climate data set, 'manufactured' from a mix of locally measured data and an existing standard data set. After consultation and reference to the CIBSE Symposium Proceedings 1988, the issue was resolved by using climate data from Dundee (Leuchars), which is similarly situated on the east coast at the mouth of a river.

Climatic data for the simulation included dry and wet bulb temperatures, diffuse and direct solar radiation, cloud cover, wind speed and direction. For the initial simulations, typical design days were selected as follows:

Summer day: 27 July (1981). This day experienced the highest direct solar gain (around $850W/m^2$); peak external air temperature of 23^oC and a mean wind speed of 2.5 - 3.0m/s (south-westerly).

*Winter day***:** 11 January (1981). This day had a low solar radiation levels (peak $60W/m^2$); minimum temperature of -2^oC and a maximum of 3^oC and a mean wind speed of 6.0m/s (south-westerly).

It was agreed that 'design days' should be selected to represent the typical and not unusually hot or cold conditions as this would provide a better insight into the performance of the building under general seasonal conditions. The selection of extreme conditions could result in misleading predictions that would be unlikely to occur in reality, and for which plant systems would not be designed to cope under normal circumstances.

Materials Information

The design team supplied a materials specification and a construction database comprising details of two types of external walls, the ground floor, roof, internal wall and ceiling constructions was developed for the initial study.

Casual Gains

A reasonable assessment of internal gains was considered vital for assessing the performance of the building. Gains from internal lighting and occupants can usually be estimated fairly readily. However, actual gains from office equipment such as personal computers and photocopiers are often more difficult to obtain. Advice was taken from a number of sources (BRECSU 1998) and it was agreed to use equipment heat gains of 21W/m^2, lighting gains of 10 W/m^2 and the following weekday occupancy profile with a maximum of one occupant per 15m^2 :

Hours of occupancy	*Level*
0800 - 0900	50%
0900 - 1200	100%
1200 - 1400	50%
1400 - 1700	100%
1700 - 1800	50%

The final lighting load of 10 W/m^2 was based on a reduction of almost 50% of the installed lighting level of 18W/m^2 due to a stated design intention to extract air from the ceiling plenum, which reduces heat gains from lighting significantly.

Zoning and boundary conditions

Experience suggests that the number of zones should be the minimum consistent with the level of performance analysis required (see 3.5.1). The Phase 1 exercise was intended to provide the design team with an indication of the likely performance of the building and not to look at issues in detail. The building model was restricted to the minimum number of zones possible, dictated by straightforward boundary conditions as far as possible. This is discussed further in the next section.

Simulation procedure: Phase 1

Given the repetitive nature of the building sections, it was decided to construct a geometric model of one of these in detail, rather than to build a model of the whole building. It was agreed that generation of a model of a representative section (see *figures 3.6 & 3.7*) would be satisfactory to allow extrapolation to the whole and also would permit more detailed studies of specific issues at a later date. The zoning strategy was decided by the physical barriers between office spaces, the outside and the core areas in the building. As the design was open-plan, the zones were large and no decision had to be made with regard to combining rooms or treating them individually.

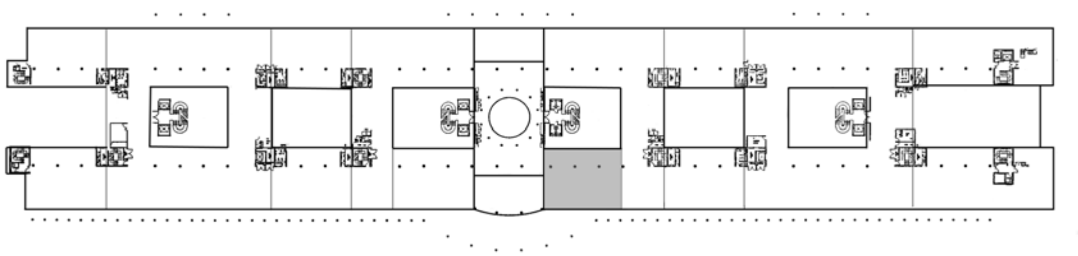

Fig 3.6: Victoria Quay - Building Plan

This strategy resulted in the 35,000 m^2 building being represented by a 22 zone, 5,300m^2 model of a typical section of the building.

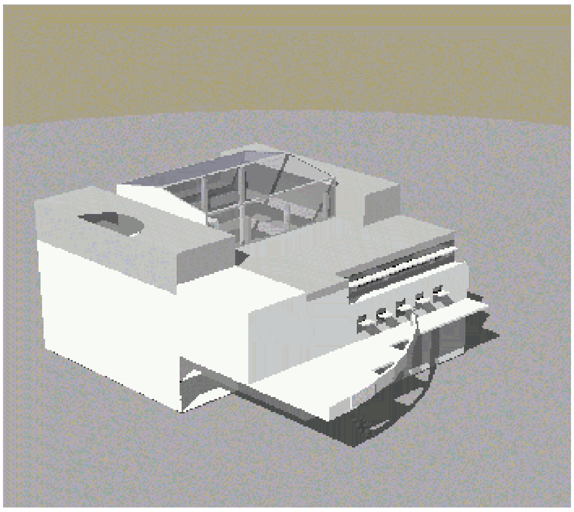

Figure 3.7 - Victoria Quay - Model View from South-East

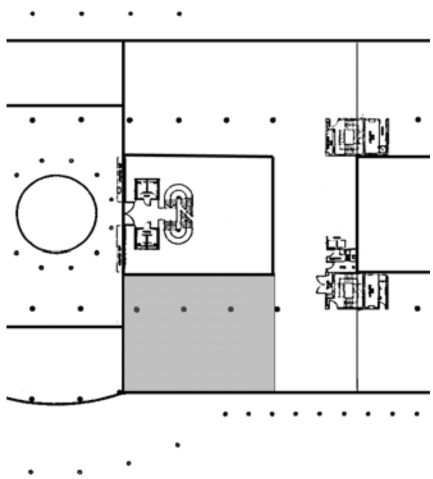

Figure 3.8 - Victoria Quay - Model Zoning Strategy - 3rd Floor

Three models of the block were set up with variations on the central space. These were analysed to determine the optimum configuration in terms of thermal performance as:

- an open courtyard;
- a fully glazed atrium; or
- an atrium with north light only.

Air flow study

The design and simulation specialist teams agreed to simulate one day in summer and one day in winter. For the winter case, it was agreed that 2 air changes per hour would be provided by mechanical ventilation. For summer ventilation, an air flow network study was undertaken to predict natural infiltration rates based on the following initial strategy in order to gauge the probable ventilation rates:

- all windows open to 150mm;
- atria high level ventilation open;
- atria low level ventilation open to courtyards.

A summertime natural ventilation air change rate averaging between 8 and 10 air changes was predicted on the basis of having most of the available windows open to 150mm, but as this could not be guaranteed, and as there was concern that this would result in excessive internal air movement, the ventilation rate used for simulation was set at a maximum 6 air changes per hour. The reliability of a completely natural ventilation system in summer would be dependent on other factors such as internal layout, cellular offices, etc. However, 6 air changes was agreed to be achievable by natural ventilation or by a mix of natural on the perimeter and forced fresh air ventilation in the core if the designers were unable to rely on natural ventilation alone.

The study approach adopted predicts air infiltration on the basis of assumed openings in the building and the climate information used for the simulation. However, as air infiltration is not only dependent on known leakage paths such as the opening of windows, but also on the quality of detailing, and on the behaviour of occupants, it could be argued that the figures adopted for summer and winter air change rates are of limited value because air ingress could be driven by other factors. The summer air change rate as predicted was deemed to fall close to the upper level of the 'preferred' range of acceptability as far as both teams were concerned. It is possible that had the figures predicted not been deemed acceptable, further investigation would have been recommended. However, 6 air changes was accepted as a natural ventilation level on the presumption that should the level rise much above this, then discomfort, disturbance of papers, etc., would encourage occupants to close windows.

Thermal studies

Thermal studies were conducted for the selected summer and winter design day conditions to predict the performance of the building on extreme days, to examine the impact of various courtyard configurations on the ventilation strategy and to assess comfort conditions and overheating risks within the offices. Simple (*ideal*) control strategies were set up with no cooling in summer and as much heat as required in winter. A time step of one hour was selected on the basis that this would be adequate to show general behavioural trends. Climate data, casual gain and materials information were all selected in accordance with the method outlined above.

Summary of results: Phase 1

<u>Building form</u>

Courtyard Design - Initial summer simulation predictions for the building with a courtyard indicated that during the day the internal temperature would be 'controlled' by natural ventilation at around 4^{o}C above the external temperature. However, detailed comfort assessments predicted a high risk of occupant dissatisfaction due to high temperatures late in the afternoon. The internal temperature was predicted to be particularly sensitive to the level of internal heat gains.

Fully glazed atrium and atrium with north light - The effect of maintaining the same ventilation strategy, but for a fully glazed atrium, was predicted to result in a slight reduction in peak internal temperatures compared with the courtyard case (approximately 0.5^{o}C). This would still render conditions unsatisfactory. It was predicted that there would be no measurable benefit by restricting glazing to a north light arrangement to reduce solar gain.

Thermal inertia

The initial summertime studies predicted that maximum zone air temperatures would occur outside of the occupied period, at around 8pm, indicating an approximate time lag of 4 hours. Simulations allowed for daytime ventilation only, with systems shut down at night. It was found that low air infiltration rates overnight would restrict the dissipation of heat built up during the day, resulting in a warm start-up the following morning. This highlighted the potential benefit of 'purging' the building overnight with cooler outside air.

Several ventilation rate options and the free cooling effect of using underground culverts were modelled to assess free cooling by purging overnight. This was effected by defining a fixed ground temperature and 'drawing' air through concrete ducts defined by zones in the model to establish the additional cooling effect. Day and night time studies showed that diurnal temperature swings could be reduced if ingress of warm air during the day could be restricted and high ventilation rates used at night to pre-cool the building. In other words, fresh air ventilation should be restricted when outside temperatures are high: the greater the fabric cooling at night, the longer the impact of free cooling the next day.

To avoid introducing air at a higher temperature than the 'pre-cooled' early morning internal space temperature, the team agreed to assess the effect of delaying the introduction of fresh air ventilation, (see *Simulation procedure: Phase 1* above) mechanically or naturally introduced until the internal temperature rose above a certain level (say 24^{o}C). The predictions suggested that this would have a beneficial effect on temperature and comfort levels in the space and that adopting this strategy could result in substantial savings in ventilation plant running costs.

Shading studies

In order to begin to assess the impact of solar gain on internal temperatures, a crude shading study was conducted by modifying the model geometry with the addition of 'physical' rectilinear overhangs. It was predicted that the effect of adding such shading devices to all except north-facing glazed areas would result in slight improvements in comfort levels. As a result of this exercise, further, detailed examination was recommended to investigate the most appropriate means by which shading should be effected, as the method employed in the model at this stage was not 'specific'.

Conclusions: Phase 1

In summer, it was predicted that the use of night time ventilation purging would reduce internal air and fabric temperatures by around 2^{o}C, thus providing free cooling early in the day and that this would help to achieve comfort conditions and performance objectives during the occupied period in the office areas. It was predicted that if this was carried out, internal temperature should not exceed the requirement of the brief (maximum 26^{o}C for not more than 100 hours per annum). Significant benefits in running costs could also be achieved by delaying the introduction of fresh air mechanical ventilation until the internal temperature reaches the outside air temperature.

In winter, the proposed heating system and mechanical ventilation were predicted to maintain most areas of the building at adequate comfort levels based on the 2 air changes per hour modelled, and the use of a fully glazed atrium in winter was shown to reduce heat losses and would act as a pre-heat/ buffer zone for ventilation.

Simulation objectives: Phase 2

The Phase 1 study was undertaken to predict general trends in the performance of the building under typical conditions in summer and winter and assessed the building in large zones without considering specific issues in detail.

From the Phase 1 exercise, areas identified where further study could be beneficial were the provision of advice to the design team on:

- detailed design of shading devices and selection of glazing system while avoiding overheating risk;
- the design of a false ceiling that would not impact adversely on the thermal inertia benefits of the concrete floor slab predicted in Phase 1;
- the impact on comfort, daylight distribution and ventilation of the introduction of internal partitions to create cellular offices on the periphery of the building as outlined in the section *Identification of design questions* above.

Simulation procedure: Phase 2

Following the Phase 1 study, it was deemed necessary to model the building in greater detail in order to examine fabric issues, detailed shading features and variations in environmental conditions in large volumes, achieved by splitting these into smaller connected zones. In order to examine these more detailed questions, for Phase 2 an 80 zone model was developed, allowing further sub-division of the spaces to study the effects of partitioning and the development of vertical zoning. The original model assumed clear float, double glazing in a simplified manner. In the new model, this was replaced by an explicit representation, which accounted for angle-dependent optical transmission and absorption within the glazing layers, and which included the ability to incorporate and control the operation of blind systems.

Shading and glazing

The addition of *brise soleil* to south, east and west facades, vertical shading devices, between-pane blinds and a comparison of low emissivity double glazing, triple glazing and clear float double glazing were considered at this stage.

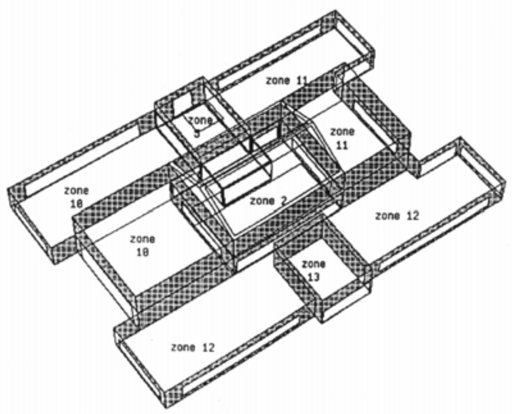

Figure 3.9
Part-Model - Revised Zoning Strategy

Figure 3.10
External facade photo showing shading devices.

Thermal inertia

As the design developed and interior finishes were decided, simulation was used to assess the impact of design changes to the fabric and the effect on thermal performance of adding a lowered ceiling below the concrete soffit. By dividing the office space vertically into three zones, with one zone above and one below the ceiling finish, an attempt was made to predict movement of air between one zone and the other for a system with a floor supply and extract above the ceiling.

Ventilation

Increasingly, requests for individual offices, rather than a fully open plan arrangement were made by the client. Simulations were therefore carried out to compare open-plan spaces versus modular offices.

Results & conclusions: Phase 2

The shading study indicated that the provision of *brise soleil* would be of benefit on the south facade, of limited benefit on the east, and that west facing rooms would require additional solar protection. Triple glazing was compared with double glazing with low emissivity (low-e) glass for both summer and winter performance. The results indicated that while in winter both performed similarly, in summer, low-e glazing was predicted to present a greater risk of overheating - due to the fact the low-e glass reduces heat loss in both summer and winter. This can present a problem in summer when heat retention is seldom required. Between pane blinds were recommended for local shading and glare control.

It was evident from the results that the high thermal mass of the structure and the passive shading devices would have a considerable influence on moderating the internal climate. It was predicted that in order for the thermal mass in the ceiling to perform as intended, the slab would need to be exposed to rising warm exhaust air. This was studied in some detail and the inclusion of a shadow gap within the ceiling tile arrangement which would leave at least 25% free area to allow air movement upwards to the slab above to dissipate heat was recommended.

The impact of the addition of peripheral offices was dependent on the extent of the cellularisation. Simulation predicted that this could have a significant effect on air distribution in some areas. As the magnitude of the effect could not be assessed with any degree of certainty, the decision was taken to adopt a mixed mode system supplying 4ac/h to the core all year round but to permit the opening of windows for localised fresh air supply.

Phase 3: final design

Phase 3 involved simulating the final design of the building and producing figures for overheating risk and energy consumption. Details of the final design with feedback from the building after occupation are as follows:

Winter: the building is mechanically ventilated, on the basis that controlled mechanical ventilation will reduce the need to open windows and thus the increased heating load associated with cold air ingress will be minimised. A perimeter heating system was provided although the results indicated that general casual gains from occupants, solar gain and electrical equipment might eliminate this need beyond a certain level of preheating provision, even in winter. Feedback from the occupants, so far, indicates that the perimeter heating is seldom required.

Summer: the building employs a mix of natural and mechanical ventilation during the day. At night the ventilation system is used to purge the low temperature night-time air through the building, thus cooling the structure.

The initial studies established that a central atrium could achieve a significant energy saving over the winter period and should not affect the natural ventilation of the building during the summer. The building was predicted to perform satisfactorily as a non-air-conditioned building, with no area exceeding 26^{o}C for more than 52 hours during occupied hours.

The final solution incorporated most of the architects' original concepts and optimised thermal performance without compromising the practical requirements in terms of space planning. Features adopted included a heavyweight inner leaf to provide mass to external walls; triple glazing with blinds and shading devices on walls exposed to solar radiation.

3.5.7 Case study outcomes

The following conclusions are drawn both from the application of the simulation methodology to the case study outlined in *3.5.6* above, and the experience gained from simulating a large number of buildings from 1987 to 1998.

The simulation of buildings is a design-specific exercise and, as such, the approach will vary from project to project. The case study illustrates how the simulation guidelines set out earlier in this section were applied by external specialists on a variety of problems, under the supervision of an independent specialist researcher. While general procedures can be applied, every project is different and therefore the application of the guidelines was often modified to suit the issues analysed.

There is no single way to undertake a simulation assessment of a building. Guidelines should be regarded objectively and applied with a degree of flexibility depending on project constraints. In the real world designers are seldom working within an ideal framework and this has to be taken into account. While it is preferable for designers to consider the potential benefit of simulation at the earliest possible stage, this is not always feasible for a variety of reasons:

- if the simulation team is involved early in the design process, then the benefits of simulation at various stages can be discussed objectively and a study conducted as, when and if appropriate. In this case simulation will be included at the ideal stage(s). However, more often, this does not occur, and simulation is only considered once the design is fixed;
- cost constraints may affect the issues examined and a building study may be carried out differently depending on whether the cost of a simulation exercise was included in the original budget or not. Often, an unforeseen problem arises that necessitates the consideration of modelling at a late stage and which was not within the agreed costs. This would obviously be tackled differently from the case where the same problem was anticipated and costed from the outset;
- time constraints may affect when, how and whether simulation can be applied, and this can result in a problem solving rather that design optimisation approach; and

- other constraints such as capital cost, site related issues, refurbishment needs and so on, mean that many projects commence from a less than ideal starting point and so design optimisation is not always the objective.

It was found that simulation is most effective when there is sufficient flexibility within the design team and in terms of time scale to allow interaction between designers and modellers throughout the length of the design process. It is also important that the views of all members of the design team are taken into account to avoid problems with potential design modifications. If the design is at an advanced stage, simulation may be undertaken on the basis of a constrained or prescriptive brief. In a case such as this, all options may no longer be available for analysis and again the exercise becomes one of problem solving rather than design optimisation. Alternatively, with experience, it becomes apparent that while design guidelines are of limited benefit in non-domestic buildings, there are general trends - and so it is not always necessary to model everything. Some aspects of projects are more typical than others.

Notwithstanding the fact that simulation can be of greater benefit at the early stages of the design, in this case study the impact of the client's decision to add a significant number of cellular office accommodation at a mid-point in the design had a significant effect on the nature of the study as a whole, in that the building could no longer be analysed as fully naturally ventilated. Given that the extent of peripheral offices could not be confirmed at that stage, the design team was forced to look for an alternative low energy solution and it was decided to proceed on the basis of a mixed-mode ventilation system. In this case, despite involvement at an early stage, the simulation team did not have a real opportunity to work through the design process as an integral part of the team, influencing the final form and materials specifications as might have been expected at the outset.

In summary, it was established through the three stages of the first phase of this research, over more than ten years, that often, even when energy and simulation were considered from the beginning, factors other than design - such as cost control, value engineering, time and site constraints and client demands and expectations of the building – will ultimately drive the project and so simulation may have less of an impact than might be anticipated. Simulation should not be regarded as a panacea but as a mechanism to shape a design that relies less on plant to attain the desired environmental conditions. Designers at this time were also becoming aware of simulation's potential, uses, benefits and limitations.

This work began the process of developing a quality assured structure for the application of simulation in practice, which holds true in many cases, but which should not be applied rigidly to all projects as each case will differ. Experience suggested that simulation should be applied with due regard to design project constraints and used as a foundation on which to build a better picture of how the building might tend to perform in reality. In the absence of integrated modelling tools, it also confirmed an emerging need for the development of a mechanism that would facilitate the design team's ability to observe the outcomes of sensitivity studies in terms of knock-on effects of design changes in an integrated manner. For example, in the mid-late 1990s, the impact on daylight quality of façade changes undertaken to alleviate overheating could not be viewed simultaneously, which to an extent defeated the purpose of undertaking such a sensitivity analysis in the first place.

This work highlighted the fact that in the absence of integrated performance assessment, there was a need to be able at the very least to view the results of separate simulations simultaneously in one place, in an integrated performance view. While research work was already underway to explore the possibility of using an integrated performance view to in order to inform judgements as to the impact of design changes, the research fed in to this by informing researchers as to the key issues and ways of presenting information to different audiences. The work is enshrined in the CIBSE Applications Manual AM11 Building Energy and Environmental Modelling (CIBSE 1998), and gave rise to an associated checklist for the use of simulation in the design process. This is outlined in the following section.

3.5.8 Checklist for simulation procedure

<u>Data preparation</u>

1. Study available drawings and establish the designers' energy and environmental performance aims, both for the building as a whole and for any specific features that are likely or are intended to impact strongly on performance. By drawing on experience and from simple calculations, develop expectations of the simulation results. Check the availability of previous simulation exercises with similar buildings.
2. Develop a project plan to achieve the modelling objectives. This should include case-specific requirements such as the reference building to be used, the level of

detail, the design alternatives to be studied, occupancy scenarios, and climate sequences.

3. Gather information related to the project such as maps, site photographs, building plans and sections (even if only sketches are available), notes on materials and use.
4. Decide on which part of the building to model and how to zone the model. It is useful to sketch out the model and (usually rough) geometry in order to confirm the zoning and the potential level of geometrical detail within zones. Tracing paper overlays of plans and sections are particularly effective. Consider how the model may evolve in the future.
5. Determine the relevant site and climate data.
6. Determine input data requirements and check available sources of information. Develop databases of constructions, glazings and internal gain profiles. Doing this before the geometry is entered allows zones and surfaces to be associated with their relevant properties as they are created.
7. Create the geometrical representation. Adopt naming and ordering conventions for the composition of zones. If these are known by others in the design team, quality assurance is enhanced. Where a model is made up of a number of similar zones, check whether one or more of the zones can be copied.
8. Identify opportunities to test design alternatives within the same model. For example, when evaluating alternative glazing systems in a simple model with few zones, it may be possible to copy these zones, edit the glazing properties and simulate the reference and design alternative simultaneously.
9. Determine the importance of shading, and include this in the model if necessary.

10. Back-up the model at regular intervals during model creation to insure against catastrophic equipment failure. Document the model and assumptions made as it develops so that colleagues can ascertain what has been done.
11. Attribute the surfaces with constructional and optical data.
12. Assign internal gains and their scheduling. In some programs, it is possible to assign common values to more than one zone.
13. Assign representative ventilation rates and idealised plant and control.

<u>Simulation and analysis</u>

1. Decide on appropriate computational parameters such as time steps and pre-conditioning period.
2. Undertake initial simulations and analyse results. Observe the predicted temperatures and heat fluxes, and determine the dominant performance factors. Carry out selected sensitivity studies and other quality assurance checks to ensure that the model is generating sensible predictions. Check that the results are in line with initial expectations, and if not then try to determine the reasons.
3. Increase model resolution as necessary. For example, include more detailed air flow and/or plant systems and control. Again, confirm that predictions are in line with expectations; and if not the reasons for any divergence. Always analyse underlying trends and causes. For example, if the aim is to determine peak room temperatures, also check at what time the peaks occur. As a further example, environmental controls are sensitive to feedback between sensors and actuators, so it is worthwhile investigating the performance over short time intervals instead of relying solely on hourly averages.

4. Simulate and analyse the agreed design variants. Given the small marginal cost of simulations, it is often appropriate to carry out additional runs to investigate sensitivities and possible design changes. Multiple runs can often be automated.
5. Interpret results in relation to informing design decision-making. This is a task that can be facilitated by the design team depending on design team members familiarity with the simulation process. Novice users/ designers who lack experience in simulation will require results to be presented in a pre-processed manner, whereas as experience grows, designers insights will assist the interpretation of results.

The issues of analysis and interpretation of results are discussed further in sections 4.4.1, 4.4.2 and 4.4.3 in respect of Quality Assurance, Simulation Procedures and Performance Assessment Methods.

Reporting

1. Present simulation outcomes at a design team meeting. Assumptions made should be confirmed, the results discussed in the light of the experience of the design team, and decisions made regarding additional work.
2. Repeat the above steps as necessary until the design team are satisfied.
3. Write the project report and circulate the draft to the design team.
4. Complete documentation and archive the model.

3.6 Outstanding issues

The previous sections define procedures for the selection of specialists and a methodology for the use of simulation in the design process. While these are important issues, in the absence of a support structure, these measures alone will not ensure effective use of simulation in practice. As raised previously in chapter 2, section 2.2, fundamental changes to the way practitioners approach the design process are also necessary, most importantly there is a need for:

- appropriate in-house working practices;
- quality assurance procedures;
- the ability of simulation to deliver what designers need; and
- addressing the need for better user skills and training.

3.6.1 Appropriate working procedures

There has to be a recognition of the need to change the way a practice operates. This would include not only the adoption and application of a methodology such as that outlined above, but an attitudinal change that requires co-operation between senior practitioners, consultants and staff is also critical to ensuring that simulation objectives are not compromised by the mechanistic application of procedures. It is not acceptable for someone within the practice to be *'the simulation expert'* detached from the process. Whoever is responsible for undertaking the work has to be part of the core team, otherwise design opportunities will be missed.

3.6.2 Quality assurance procedures

Allied to the adoption of a methodology for model building and use of simulation in practice is the need for a quality assurance system that, in support of the fail-safes in the methodology that supported model creation and testing, documents the process in order that all assumptions and why these were made remain apparent months or years down the line. This has to be rigorously applied as the model evolves in order to ensure that the project can be resurrected by someone not involved in the creation or testing of the original. Although implied in the procedures for selection of specialists and in the outline simulation methodology, this issue remained unresolved at this time.

3.6.3 Ability of simulation to deliver

Despite the attestation in this chapter that the adoption of a simulation based approach is necessary if designers are to address the design questions that arise when meeting the requirements of legislation combined with new technologies and innovative architectural propositions, which may or may not mitigate climate change, designers still face challenges in using simulation effectively. In reality, designers need answers to straightforward questions such as: *Can simulation deliver what I need?* and *How do I use the outputs to inform my design?* And they need these answers quickly and affordably in order to minimised disruption to their day-to-day work practices. This once again raised the issue of the need to develop standardised performance assessment methods in order to support and direct the user's inquiry and also the need to assist users in interpretation of outputs (as introduced in section 2.2.4). Although the ability to simulate a number of design parameters simultaneously in an integrated manner was at this point in time in it infancy, the need to be able to assess multiple issues within a single integrated performance view was already apparent as highlighted above.

3.6.4 User skills and training

The development of simulation methodologies and QA systems alone are not sufficient to address the needs of potential practice-based users. While experience of designing buildings in the real world is invaluable in the creation and evaluation of simulation outputs, performance assessment methods and quality assurance procedures are not a substitute for training. In terms of building a model, simulating and extracting useful results, a simulation expert can develop a building model, simulate, and produce results in a fraction of the time of an experienced designer with limited simulation skills.

3.7 The next step

The activities reported in this chapter were successful in supporting the delivery of quality assured advice to the professions, and in developing a methodology for the application of simulation. However, the real cost of employing a specialist was regarded as prohibitive, and the only way to address this was to encourage the use of simulation on everyday projects in-house by design teams. Underlying this was a lack of confidence among practitioners to produce quality assured simulation work in-house. From the many projects undertaken, issues relating to how design teams work and how simulation can be integrated into the process were explored in detail. This work created the perfect platform for the next phase, the development of a support structure for the use of simulation in design practice that would advance the uptake of simulation as a mainstream design activity.

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Chapter 4 – Embedding Simulation in Practice

Building on the findings of the previous phase of work, the research now moved to embedding simulation in practice. The work was undertaken with support from the Scottish Government through the Scottish Energy Systems Group (SESG).

This phase of research commenced in 1999 with the objective of transferring simulation into design practice by removing the remaining obstacles and barriers to uptake imposed by current work practices: a steep learning curve, poor ease of use, fear of user error, discontinuity between program capabilities and the scale and complexity of real buildings, demanding resource requirement, credibility of predictions, need for specialist computing equipment and, most importantly, the lack of a supportive network. The premises underlying the research were:

1. that in the context of energy systems design there existed an urgent need to reduce the gap between system specification and life cycle performance assessment;
2. that existing modelling systems provided a means to bridge this gap and so reduce the design response time;
3. that the ability to address the complex dynamic interactions, and multi-variate issues inherent in energy systems would enhance product robustness;
4. that there existed a need to move such analyses towards the early design stages, to better support design concept synthesis where the potential impacts are greatest and least costs committed;
5. that the early design stage activity could be supported through the creation of appropriate computer-based, decision-support environments;

6. that a critical mass of specialist energy modelling knowledge currently existed in the UK which was in danger of being dissipated due to withdrawal of government support;
7. that computational tools and facilities required by the industry and the expertise to use them will only be developed through collaboration between the user and developer communities;
8. that virtual design technologies will enable co-operative working between disparate partners.

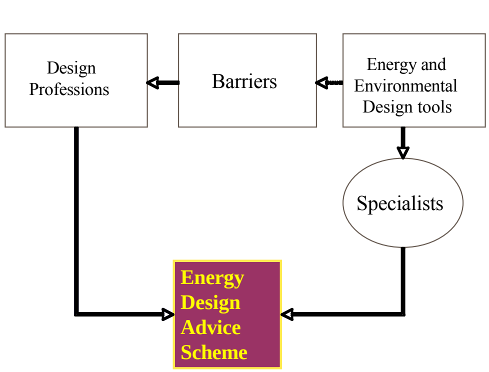

Figure 4.1 - the EDAS approach, supporting use in practice - technology 'push'

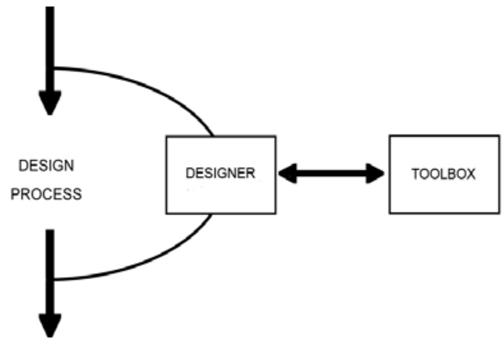

Figure 4.2 –simulation detached from the design process: a plug-in 'toolbox'

4.1 Towards design process integration

The approach to providing simulation based advice described in the previous chapter relied on the services of simulation specialists who remained separate or detached from the design process – like a kind of plug-in toolbox (Figure 4.2 after MacCallum 1993). As illustrated in figure 4.1, this approach relies on the flow of information into and out of an intermediary, and thus gives rise to a delay between the delivery of the simulation results and the evolution of the design hypothesis. It can also result in missed opportunities for exchange of innovative ideas as, with the exception of exceptional cases, there is little or no scope for ongoing dialogue between the designers and the specialists, who would generally work in separate offices, coming together only to discuss what needs to be done, what were the outcomes and how to interpret these in design terms.

Successful outcomes were possible under this system, but there was a growing frustration on both sides, resulting from the perception that simulation should be able to better inform the process – assisting the evolution of designs through the joint exploration of *what ifs*?, which might lead off in many unexpected directions. If the simulator and designer do not uncover such scenarios together – there is no opportunity to go down these alternative routes. There was also an associated issue related to the fact that those procuring simulation services, were protected from the risks associated with user error, results interpretation and lack of confidence in simulation tools and themselves as simulators. In addition, to date, users were unwilling to pay the true cost. It was clear that despite significant moves forward, most of the barriers to deployment in practice remained. However, there was a willingness to trust the tools to others while benefitting from the outputs and this was a major breakthrough, provided the other issues could be addressed.

At the commencement of this phase of the research, two core issues were identified as critical to the pursuit of in-house deployment: quality assurance of the related models and appraisal results, and in-house procedures for the management of simulation. Fundamental to the success or otherwise of the application of simulation in design practice is not the existence of such procedures, but the rigour with which these are applied (CIBSE 1998, McElroy and Clarke 1999). The previous research phase had begun to address the former, but the latter remained an issue that was preventing those design practices who wanted to move forward, from doing so.

4.2 A computational approach to design

The SESG was built-up to advance the use of simulation through the creation of a supportive network for deployment in practice. The initiative had several mutually supportive aims. In addition to promoting and supporting the use of tools for the simulation of the performance of buildings in the context of design practice, the aim was to develop the competitiveness of those energy sector businesses involved in the design of the built environment in Scotland by providing a support service that would bring the professions together through the creation of new opportunities for collaborative working. The long-term objective was to help built environment sector companies to evolve in three important respects through:

– enhanced performance robustness through integrated design;
– better productivity through reduced design development times; and
– improved competitiveness through the greater potential for inter-organisational collaboration.

With regard to positive environmental impact it was envisaged that the effect of up-skilling would:

– raise the capacity of architects and engineers to compete effectively through improved business processes, specifically through embedding of innovative IT-based design tools and greater innovation, research and development;
– increase awareness of environmentally sustainable building design practices, and

– promote the implementation of sustainable processes and products in the built environment.

From a research point of view, it was envisaged that the impact would be:

– to enhance the relationship between built environment companies and higher education establishments, thus investing in the Scottish knowledge economy; and

– to facilitate knowledge transfer from research to practice.

This research phase was founded on the belief that the industry was now ready to commence the process of adopting a computational approach to sustainable energy and environmental systems design whereby simulation tools are fully integrated within the design process (Figure 4.3). This would allow them to undertake energy and environmental analyses in-house as a matter of routine.

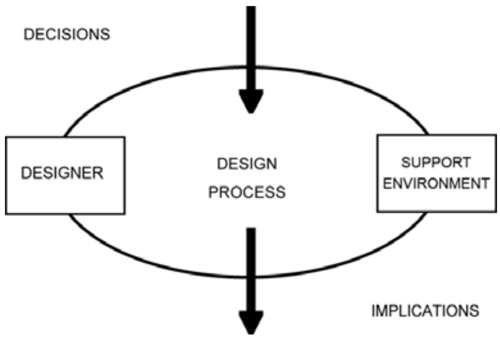

Figure 4.3 – Simulation fully integrated into a computer supported design environment

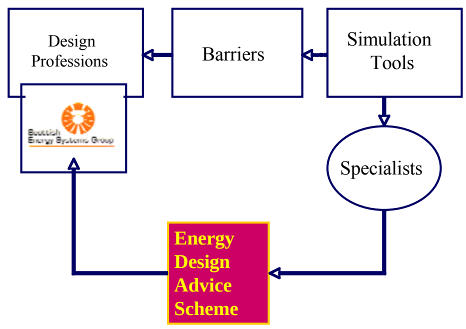

Figure 4.4 – the SESG approach embedding simulation in design practice – 'technology pull'

Fundamental to the validity of this phase of the work is the belief that simulation tools have reached a level of maturity that enables them to be readily deployed in practice.

Prior to this, design teams had gained access to simulation specialists on a consultancy basis and despite resulting in substantial energy savings, the approach had several shortcomings: although subsidised, the use of specialist consultants was an extra cost; design times could be increased while waiting for reports; and the design team was not able to freely explore options as the specialist consultant directed the process. It was envisaged that this next research phase would address these shortcomings by moving simulation from the domain of specialists to a routine design process activity by creating a support mechanism that would encourage a 'technology pull' from the industry (Figure 4.4).

This second phase of the research had a number of well-articulated aims, but the key one was to embed integrated performance analysis in design practice as part of the day-to-day design process. In so doing, the project invested in the Scottish knowledge base, enhancing the services of its member organisations by raising their productivity and providing them with a means to address the complex issues underlying the design and operation of a sustainable built environment. This was done by giving possible users the opportunity to experiment and evaluate the suitability and potential of various simulation tools to meet their needs by seconding experts to the design team, to work with them within the timescales of their day-to-day work practices. Compared with the earlier phases of the work, where specialists undertook work separately, outside of the process, this initiative invited (or challenged) consultants themselves to take up these advanced tools so they might discover their potential for themselves, based on the hypothesis that integrated simulation can provide useful design support information '*quicker, cheaper and better'* than the traditional methods it seeks to replace. The research was undertaken on the understanding that in this phase, simulation support staff would not seek to impose a particular way of working on the organisations they supported, but instead would assist them in their own chosen way of working and decision processes, thus tailoring the service offered to their individual needs.

The premise was that the application of design tools in practice offers the potential of improving the building stock by bettering its performance – raising comfort levels, reducing fuel poverty, and lowering its environmental impact including carbon dioxide emissions – leading to improved health, well-being and productivity for occupants and making buildings more environmentally sustainable.

To achieve these objectives, the main activities were:

- the formation of a business network or ‘industry club’ of small and medium sized enterprise built environment professionals;
- organising a dissemination programme of newsletters, seminars, workshops and training sessions, and
- making simulation tools available to companies within a fully supported environment and within their own offices on live projects.

To this end, mechanisms were established to enable design teams to undertake rigorous performance appraisals, in-house and routinely. Because the technology was now accessed directly, as opposed to via contracted specialists, it was expected that the savings achieved during the previous phase of the research could be substantially improved upon: estimated cumulative energy savings to the year 2008 of £172 million, 285,000 tonnes of displaced CO_2 per annum; and the improved capability of the industry through the provision of explicit performance assessments (ETSU 1998).

4.2.1 Addressing the changing needs of industry

Like the previous research work, this phase employed both traditional and innovative dissemination techniques. However, in order to meet the changing needs of the industry and the objective of creating a pull for the technology, the emphasis on what topics were addressed changed significantly. Each month a topic was selected and over the course of that month, themed, complementary events were delivered to the industry with a view to informing; inspiring and encouraging the industry to innovate. Seminars focused on big picture issues such as climate change, renewable energy, air pollution, energy labelling or pending legislation changes – all topics that could be addressed or would imminently be addressable by simulation. These were followed by workshops to explore issues through focus groups of interested, like-minded individuals, at which experts would demonstrate and offer hands-on experience of modelling tools that addressed as many of the topic areas as possible. The aim was to address the range of issues that impact on sustainable development and to point out the role that simulation could play in each case.

As part of the monthly activities, on-site training was introduced during which company personnel could obtain hands-on instruction in modelling tools appropriate to the topic being addressed that month. The aim was both to develop the modelling skills of technically orientated employees and to provide management with an appreciation of the technology's capabilities.

In terms of innovative projects:

- in-house assistance with the application of featured tools within actual projects (including the loan of a suitably configured computer). This consisted of exclusive access to an expert simulator, seconded to the design team through a mechanism known as a supported technology deployment.

- the establishment of advocacy groups to explore key issues and elaborate future actions;
- the elaboration of practical quality assurance procedures for use in practice;
- the further development of simulation procedures for use by practitioners; and
- the development of integrated performance benchmarks.

A Supported Technology Deployment (STD) is key to the innovative aspects of the project in that it provided in-house training and support for model use. This was seen as the best way to eliminate the remaining barriers to effective technology deployment. The last three devices exist to support this activity by facilitating discussion and providing guidance on simulation procedures and results interpretation.

In this way, members could identify the specific issues that currently present obstacles/ opportunities for their particular business, allowing them to develop new skills in tools that could assist them to address these issues. Through this initiative, members received help in translating simulation outputs into practical decisions that could be implemented in their design work, all on a repeating monthly basis. The offer of in-house assistance (through the STD mechanism), with tool deployment proved particularly successful, with some companies choosing to purchase a loan computer in order to ensure that their newfound work practice can continue unhindered by IT-related problems.

4.2.2 Traditional approaches

In addition to the standard monthly activities outlined above, information was disseminated via a newsletter (HotNews) and a dedicated Web site (www.sesg.strath.ac.uk). Regular presentations to professional events organised by others also enabled dissemination to the wider construction community. These took the following form.

1. Newsletters

Eight newsletters were issued to over 500 individuals since its inception in early 1999. The newsletters cover six sides and are presented in full colour. Each contains a *'What's New'* section, a leading article, case studies, reports of past seminars, workshops and training events, membership news, and a factual page with contact details and forthcoming events.

The newsletter has been seen as an excellent way of keeping members, and others to whom it is distributed, informed about the progress of the initiative, and highlighting key topical design and legislative issues to the industry at large. It has been issued intermittently, in response to perceived needs in order to provide support in specific areas, in that, as an area of concern was voiced by members, the arising need was dealt with by devoting an issue to key areas of interest, this allowed the initiative to respond incrementally as issues ramped up:

Issue 1. 'Saving energy by design', introduced the initiative by advocating a simulation approach to design; highlighted where to obtain advice on the tools available; provided a detailed case study on a state of the art application of simulation and started off the frequently asked questions section with in-house ideas on what the industry might need in order to prompt responses.

Issue 2. 'Simulate it!' demonstrated to the industry how simulation was necessary to respond to the new and emerging challenges of innovation and legislative requirements; introduced the breadth of tools available and gave advice on here support could be obtained by those not ready to go it alone.

Issue 3. 'Getting started', offered advice to those who were keen to begin the process of moving the tools in-house in terms of how to obtain the support to build the necessary skills; gave advice on simplified tools to allow them to start the process immediately and to spur them on, and reported on how one company had joined SESG and was already undertaking simulation as an in-house activity.

These and further sample newsletters are included as Appendix 7.

2. Website – www.sesg@strath,ac.uk

The website provides an overview of the activities of the group, the programme of events, links to web sites of organisations offering various software packages, descriptions of the various services and university facilities available, as well as acknowledgements to the funding bodies, and contact details.

3. Email notification of events

Regular emails have been issued to around 500 members and interested parties notifying them of the programme of events and forthcoming seminars, workshops and training events in the traditional way, and linking up with other organisations including the RIAS, BRE, CIBSE, the Scottish Ecological Design Association, Scottish Solar Energy Group, and so on in order to consolidate the role of simulation within the bigger picture.

4. Conference papers

Together with the members, nineteen papers have been published at national and international conferences. Typically these set out the potential for simulation and offer some general observations about procedures, quality assurance, and risk, and the later ones discuss the breaking down of barriers and the development of quality assurance procedures for tool use in practice. More significantly, they demonstrate a newfound willingness on behalf of practitioners to become involved in presenting the industry's view in a traditionally academic arena. In terms of the potential for simulation to contribute to climate change mitigation and improved built environment performance generally, this is an important step forward in reducing the risk of simulation achieving less that it full potential due to academics working in isolation from the real world.

Taken together, these technology transfer mechanisms have:

– imparted insights into simulation issues relating to sustainable development;
– fostered skills acquisition in advanced simulation methods and tools; and
– allowed the industry to obtain on-the-job application experience within the wider design context.

The following sections outline the more innovative services offered and the measured outcomes compared with the cost of operation of the scheme in more detail. These are elaborated in the next two sections.

4.3 Access to advanced computational support

Aside from the steep learning curve associated with simulation applications themselves, and the lack of trained staff to undertake simulation work, practitioners are also faced with problems related to hardware and resources. Powerful hardware is available, but companies are often reluctant to invest for any number of resource related reasons: economic, staff, project deadlines, etc. Computational power and the software capabilities are evolving rapidly and the most appropriate time to invest in new systems is difficult to predict. This phase of the research addressed this issue by establishing a loan pool of computers fully configured with a range of relevant applications representing the spectrum of possibilities described in Chapter 2: from simplified design tools, through general-purpose thermal and visualisation tools, to integrated simulation tools and demand and supply side management tools. The aim is to be able to deliver a software ready system to members on demand in order to facilitate a no-risk evaluation in the context of a real project. This process is further enabled by the presence of specialist personnel who are trained in the application(s) being deployed. There are four key benefits to members:

- risk free access to simulation packages;
- opportunity to evaluate hardware and software prior to investment;
- reduced risk of investment in inappropriate systems;
- the presence of specialists ensures effective application.

Beneficiaries of the scheme have included; local authorities, educational establishments, consulting engineering practices and architectural practices. If appropriate, the loan machines can be purchased at the replacement cost. The pool of machines has also been used to run several training courses.

It is recognised that while delivery of a state of the art computer will not meet the needs of all, it can provide an important first step in demystifying simulation, thus moving the organisation some way towards the goal of adopting a computational approach to design. This initial access reveals the myriad opportunities available, but in most cases the participant remains on the outside looking in, able to identify the potential, but not knowing '*what to do with the technology?*'.

4.3.1 Supported technology deployment

An STD provides participating organisations with in-house training and support for model use on live projects. The development of this mechanism in this phase of the research made possible an important breakthrough in the elimination of the barriers to tool uptake. The aim was to facilitate discussion and provide guidance on simulation procedures and outcome interpretation in the context of live design projects and within the constraints of real project deadlines, thus allowing practitioners to gain risk-free access to simulation in the context of live projects and otherwise normal work practices, allowing them to identify the financial and human resource barriers to routine tool deployment. All of this was made possible by the provision of a fully configured computer, and an experienced operator to a design team for the duration of an appropriate part of a project at no cost. By placing specialists within the design team, a two-way flow of information is supported: thus simulation know-how can be exported directly to practitioners and specialists directly exposed to real design issues.

Typical examples of an STD include:

- the deployment of software within an architectural practice to allow early design stage assessment of energy and environmental issues;
- the deployment of compatible thermal and lighting simulation programs within an engineering consultancy;
- the deployment of an energy simulation system within a housing association for use, in conjunction with field measurements, to evaluate the impact of proposed upgrading measures;
- the deployment, within a utility, of software for co-generation feasibility assessment in the context of high rise housing.

This demonstrated that not only was the perceived need growing, but also, there was a developing understanding of the range of issues that simulation could tackle. This suggested that the role of simulation in practice was coming of age. In each of the above cases, to further the research, the process was observed and documented in order to highlight, expose and resolve deployment issues, as a passive observer in the process. Of paramount importance is that the specialist responded to design team needs and was not pro-active in the application of simulation. The benefits of an STD were twofold:

- practitioners gained risk free access to simulation on live projects and within normal work practices, and the industry is thus better able to identify the financial and human resource barriers to routine tool deployment; and

- specialists working from within the design team, were exposed to a two way flow of information: simulation know-how is passed directly to practitioners, and specialists face real design issues.

Thus, compared with the previous phase, although the design team had not yet taken full control of the simulation process, the implanting of the specialist in the design team, responding to their needs rather than driving the process as 'the expert', gave a new impetus to the process, with design teams beginning to drive the direction of the work. Further, in order to explore the potential impact on current work practices of adopting a formal simulation approach within an integrated design team approach, the process may involve more than one company. The following case study exemplifies the process.

Case study: An STD in a major multi-disciplinary design company

A recent series of interactions with this major company explored many of the issues raised above. The company had a history of 'buying-in' assessment services, but the had come to the conclusion that this approach was less efficient than had been originally expected. This was identified as being due to an increased burden on staff time in terms of the need to analyses and digest the assessment reports. In addition, the company had concluded that this 'out-sourcing' approach offered few options for adding value to the deliverables, or time for revisiting issues with alternative proposals. A key issue was the fact that there was little or no opportunity to learn from such a detached approach.

As a consequence of reaching this conclusion, a long-term plan to build an in-house simulation capability was developed by the Glasgow office. This required commitment to:

- up-front mid-level management buy-in;
- commitment to freeing of resources for staff training;
- mentoring of their working practices; and
- critical support for delivering useful information within design teams.

During the period of 'up-skilling', the project leader worked to change the ethos within the company towards valuing the deliverables of the team. The need for such commitment may seem obvious. However, in the past, for many companies embarking on this path, lack of management buy-in, lack of objectives/ direction and lack of effort to carve a niche for such new activity has resulted in companies giving up, and returning to traditional methods.

Due to the existence of the support facility the company overcame the barriers associated with timescales required to develop the necessary skills: from lack of trust in the accuracy of models to risk of misinterpretation of results, and is at the time of writing well on the way to developing skills to deal with the quality assurance issues related to the impacts of uncertainties and the risks associated with user error.

The process was monitored and documented to identify problems and bottlenecks in order to assist in the development of strategies for the use of simulation in real-time design. This information was reported back to the industry at large through newsletters, seminars and workshops.

Based on numerous similar experiences, the STD mechanism has proven itself to be a powerful technology transfer device, largely because training is an integral part of a familiar process and is undertaken in the real time, real scale context of design practice. Following on from a successful STD, it was not unusual for a company to acquire the featured simulation package and send staff on related training courses organised through the initiative. This is a key point for the development of the research: a serious investment in software and training is only made after the benefits of a program have been demonstrated in a commercial setting. In this way, companies are able to evaluate the appropriateness of alternative programs before making a decision to invest.

A wide range of building types and technical domains have benefited from an STD: from the refurbishment of an important historic building, through daylight utilisation in offices, to low energy school design and fuel poverty alleviation to name but a few.

Several clear messages for the research have emerged from completed STDs as follows:

- contemporary modelling systems can be cost-effectively deployed where appropriate support is available;
- the largest portion of the cost relates to staff training, not to the acquisition of hardware and software;
- a change in work practices is needed if the profession is to move to a new best practice based on a computational model of design;

- all STD recipients have reported that they anticipate no impact on their professional indemnity insurance due to the uptake of simulation; and
- interestingly, project fees are likely to remain the same despite the value added to their service. This is because access to simulation engenders the confidence to implement innovative solutions that would otherwise not be possible by conventional methods.

This highlighted that although the industry was willing to progress down this path, it still required support to change its work practices in order to do so. There was also a recognition of the fact that this was not an easy step to take and that intensive training and associated quality assurance procedures were required, particularly in the absence of instantaneous access to support. This, to an extent, contradicts the 1990s perception that the key to moving simulation into practice related to better interface design rather than to better design support.

As suggested above, besides the STD mechanism, there are two other main forms of support to businesses. Firstly, a programme of regular seminars and workshops dealing with energy, climate and sustainability issues, as well as developments in energy efficiency technologies, and forthcoming regulations and directives. Secondly, workshops and training sessions that provide hands-on introductions to modelling systems and new software tools. These were offered both through the initiative and by commercial software organisations. A plan for events was devised early on in the research which set out monthly themes – such as climate change, daylight in buildings and so on. These seminars and group training sessions often precede STD activity within an organisation, offering companies the option of 'testing the water' before committing considerable company time/ resources to an in-house deployment. STDs are discussed further in sections 4.5 and 4.6.

4.3.2 Advocacy groups

Building on the earlier work in phase 1, this phase of the research has facilitated the natural transition of simulation from a specialist domain to design practice within companies where the potential of simulation was well understood. However, understanding of the potential of simulation within other sectors was not yet well developed. Advocacy groups were set up to allow organisations to explore issues together and thereby identify opportunities for, and barriers to, the effective application of simulation in new areas. In order to ensure good user requirements capture and tool options definition, groups comprised model developers and users.

The views from advocacy groups have been disseminated through the newsletters and workshops. Typically, these groups are multi-disciplinary but focused on the needs of a homogeneous sector, e.g.:

- design practices with an interest in the same simulation package;
- the energy efficiency of their building stock;
- manufacturers wishing to demonstrate the performance enhancing impact of their products;
- and utilities concerned to effect procedures for the matching of supply with demand.

To raise the level of knowledge within the groups, a range of support mechanisms existed such as:

- dissemination of information on available simulation systems;
- applications software training;
- establishment of partnerships between group members and technology providers;
- seminars/ workshops on simulation topics;
- and the placement of students possessing simulation skills.

This provided individuals and companies that held a particular view, or who had particular reservations with an opportunity to discuss their concerns or promote their views within a wider audience, rather than having to address concerns to only academics or tool vendors who might have completely different viewpoints. In this way participants were able to move forward by overcoming barriers together, and academic and vendors as part of these groups received constructive feedback on what the industry needed and expected from tool developers.

Case study: Improved competitiveness of members of an advocacy group by adopting a simulation based approach to design

The five participants of an advocacy group focusing on the business benefits of adopting a simulation based approach were asked about the contribution to increased sales brought about by up-skilling. All four confirmed that in their view, the additional expertise and the new services they were able to offer that were gained as a result of engagement with the initiative had led to additional sales. Engineer A reported that new work had been generated and they were now selling an enhanced service in mechanical and electrical consultancy. Architect A reported that the architecture practice that he worked with were expanding their services particularly in the area of sustainability, where he believed they were now better able to talk the same language as the building services engineers with whom they work. In turn this was reported as leading to a more collaborative design approach – which was also appreciated by clients. Improved expertise in sustainability issues was reported to be helping them to win commissions and helping clients to secure project funding, particular where sustainability was an important aspect. Engineer B reported similarly that, after an evaluation of one particular software, many in the firm had now been trained in its use and the firm is now offering it as part of their range of services. Engineer C who worked with a government funding agency, said his interests were currently in using simulation to evaluate renewable energy technologies to raise confidence in their potential so as to justify grant awards more easily. Engineer D reported that his company was testing out building energy modelling software on cruise liners and has focused on software to model everything from collisions at sea through means of escape in case of fire to energy efficiency standards in the passenger accommodation areas which to date has been poor. Without support they would not have been confident to explore all of these issues. He feels that not only do they now have a edge on their competitors who do not yet uses such skills for energy or safety assessment, they also have access to a group of people working on similar issues, and this provides confidence and a sounding board for new ideas.

Although none of the five organisations was able to estimate the extent of their increased sales, they reported that by working within and advocacy group, they have developed new areas of expertise and, in consequence, won new business. Again this is very much in line with the expectations set out in the original objectives for this research phase.

It was recognised by all those interviewed, that the benefits of simulation, are dependent on the quality of the input information and the ability of staff to understand and interpret the outputs. The interviewees highlighted shortcomings, e.g. in terms of the need for better databases for evaluation of whole life– while the expected lifetimes of mechanical and electrical services were relatively well understood, there was uncertainty about other building elements; and they felt that there was scope for academics to contribute in this area in particular. This information helped to steer the direction of the ongoing research.

Supported technology deployments and advocacy groups provided the industry with access to specialists to support technology transfer and peer groups within which to explore issues arising. The following section explores issues related to the uptake of simulation in practice.

4.4 Adapting practitioner work practices

Quality assured procedures for the in-house use of simulation and a universally applicable methodology for use in practice are recurring themes in this research. The first phases of this research tackled two aspects in this respect:

- firstly, the need to have a quality assurance procedure for the selection of the most appropriate specialists to undertake simulation on a third party's behalf; and

- secondly, the need for a methodology for the application of simulation, suitable for both expert and novice users.

What was needed now in order that designers could adopt a simulation-based approach to the design process as a matter of routine were:

- quality assurance procedures for in-house use, in order to allow users to apply the methodology developed previously with confidence; and
- procedures suitable for adopting within normal work practices for the management of simulation and the associated data generated.

The procedures devised within this phase of the research are elaborated below.

4.4.1 Quality assurance

Based on experience over the previous phases of the research, the greatest threats to the use of simulation in design practice centre on the following remaining barriers:

- timescales required to develop the necessary skills;
- lack of trust in the accuracy of models;
- credibility and risk of misinterpretation of results;
- the impacts of uncertainties;
- risks associated with user error: and, most importantly:
- the lack of support available to develop the necessary skills.

The viability of adopting computer-based assessment as a mainstream design activity within a commercial environment is therefore dependent on developing appropriate working practices and Quality Assurance (QA) procedures that facilitate monitoring and documentation of the simulation work to a level that will instil confidence in users (and recipients of recommendations extracted from simulation outputs) without hampering design progress. Within this framework, co-operation between developers, practitioners, consultants and staff is critical to ensuring that simulation objectives are not compromised by the mechanistic application of procedures.

It is essential that the QA system adopted addresses all possible procedures, decisions, assumptions and data sources employed, with a degree of documentation that is adaptable and appropriate to the scale and type of the project. The primary concern within industry in this case was in ensuring that QA procedures did not impede the design process, e.g. due to delays experienced while waiting for simulation results.

New tool users can be disheartened by systems that do not adequately support model creation, documentation, archiving and retrieval. There is a risk that such systems will 'trap' or conceal errors, and unless identified first time around, this can result in the perpetuation of model inaccuracies. Hand (1999) recommends that these issues be addressed by developing a procedure that is encapsulated within an overall quality assurance procedure, but this is a complex task, (Parand and Bloomfield 1991, and Chapman 1991). This phase of the research aimed to assist businesses to evolve such a procedure by building upon the good practice established previously in the first phase of the research as reported by CIBSE (1998), and subsequently the follow-up work of BRE (Davies 1999). The procedure envisaged for transferring simulation from a mainly specialist activity into routine use in design practice has 8 stages, this has been developed and tested in practice and is elaborated below:

1. Project Initiation

Project Initiation includes the definition of the project's scope, the selection of the most appropriate software applications and the establishment of the in-house project team, including an independent advisor (in this case, the in-house researcher). Arrangements were then made for the delivery of the required application-ready hardware from a computer loan pool and the secondment of specialist staff. Importantly, the company staff set the appraisal agenda and delivery deadlines and the seconded staff served only to ensure that the simulation program does not burden the process.

2. Identification of objectives

At this stage the technical objectives are defined and responsibilities agreed between the organisations involved. At this juncture, the independent advisor’s role is to facilitate access to any new simulation packages, to ensure that misapplication does not arise from unfamiliarity and to determine any barriers to routine tool use. In this last respect, the independent advisor documents the approach taken, the tools used, the outcomes attained and the (changing) perceptions of the project team, before, during and after the process.

3. Mapping of objectives to simulation tasks

For those with little simulation experience, initiating simulation projects and identifying objectives are non-trivial issues. As most building designers are not proficient modellers there can be a tendency to rush the initial stages in an eagerness to obtain a working simulation model. In addition, the preparation of a simulation model is time-limited, in order to accommodate real-time design process constraints.

Many subsequent model construction, simulation and output quality issues stem from the fact that there is no available clear guidance as to the important features of a building model (Donn, 1999). This thesis has made some attempts to address this issue in section 3.5 and makes further observtions with a view to alleviating this issue in the remainer of chapter 4. For example, no hierarchy is given as to what issues or zones require the greatest (or least) level of detail. A lack of guidance can lead to the modeller spending unnecessary time building zones with surplus or inadequate levels of detail. The independent advisor ensures that the mapping of design questions to modelling strategy are fully considered and that a level of understanding of critical and non-critical issues is reached. In this way it is ensured that good practice will evolve over time.

4. Identification of uncertanties and risks

An important issue facing users of simulation is uncertainty. In the context of innovative design, it is the risk element that must be tested if the boundaries of best practice are to be pushed forward. Only when a parameter's uncertainty is known, can the associated risk be determined (Macdonald *et al* 1999). Perceived uncertainties and risks are documented and discussed as part of the process through advocacy and focus groups in order to build up a level of understanding of where the greatest risks and uncertainties lie, and which are of greatest potential significance. In the context of adopting a simulation approach to the design process, it is proposed here that the greatest risks in terms of impact on decision-making are: unidentified user input error and incorrect or ill-informed decision-making (see section 3.5.4 *Risk and uncertainty*).

5. Simulation procedures and maintaining audit trail

While vendors may be confident about the validity of the results produced by their program, there is as yet, no mechanism whereby this confidence can be passed to a user. Experience to date has shown that engineers frequently request simulation without any real consideration as to the nature of the problem, or indeed, what the simulation is expected to prove or disprove. By developing mechanisms that force such requests to be better considered with respect to purpose, it is envisaged that simulation users will become better able to direct their time efficiently and effectively.

Through this work it has been possible to engage with the industry to raise the level of awareness about predictive accuracy in general, and the relationship between actual and predicted perfomance predictions with a view to establishing procedures for simple model calibration and to develop a checklist approach to model/ result archiving.

6. Translating simulation outcomes to design evolution

Simulation allows designers to perceive the future reality at the design stage. This, in turn, gives them an appreciation of the potential performance impacts of intended design actions. Unfortunately, the mapping of time series performance data to decisions on design hypothesis modification is a non-trivial process. Consequently, there is a need at some stage in every simulation process for an expert/ adviser to assist with the interpretation of simulation results. Even in the case of simulations conducted by experts this step is necessary as modellers, closely involved in model creation often find it difficult to detach themselves from the process, and thus their judgment can be biased. Similarly, non-experts, without the benefit of an expert/ adviser can find it difficult to know how best to make use of results.

There is no 'quick-fix' solution to this problem, however, this phase of the research has attempted to raise the level of debate on this issue through its wider activities through its advocacy groups, seminars and workshops, and sees team working and partnership as key to successful outcomes.

7. Client reporting

The research also began to address the development of standard reporting formats based on the model instigated in phase 1. This is seen as an essential prerequisite for practitioners. As discussed in the previous section, assuming users are able to understand the performance impacts of intended design actions, it is important to develop appropriate methods for translating outcomes to a format suitable for all design team members to digest (McElroy *et al* 2003), and bringing together outputs of multiple tools if appropriate in an integrated performance view. Such reports facilitate inter-project comparison and assist with project quality assurance. By creating company specific, standardised reports, it is envisaged that the whole team will develop a better understanding of the process thus instilling confidence to question simulation results.

8. Model archiving and sign-off procedure

Good practice simulation dictates that project models be archived for possible future use. The decision on which model to archive will depend on its perceived value within the project. Building on phase 1, this phase sought to evolve the industry's views on how this might be done in a manner that supports inter-organisation use and is assisting member companies to explore these issues in practice. In respect of providing assistance with the development of specific in-house QA procedures for tool use in practice, the initiative has provided a think-tank and repository for sharing of experiences, while working in-house with companies to help them to build systems and to gain from the experience of others who have already travelled the same path.

Case study: Identification of the need to develop QA procedures in a simulation-based consultancy

The following case study relates to support given to a relatively experienced simulation-based consulting practice that sought to diversify its core competencies in order to attract a range of project types. This move was supported by the initiative, by providing a specialist advisor to assist with the integration of the new simulation capabilities as required.

The practice set out with an initial focus on one suite of software, but as it began to take on a variety of work, additional simulation tools were gradually adopted. Thus, the practice actively sought to attract, train and retain staff with a range of skills. Experience indicated that two broad categories of skills and experience were required - those with domain skills and an intuitive grasp of how to approach complex tasks and graduates who are able to quickly acquire skills and adapt to non-traditional work practices and project demands.

It became clear to the practice that simulation-based consulting is typified by a mix of active, pending and dormant projects. It is exceptional for staff to be working on a single project. Senior staff may be called upon to advise on aspects of a score of projects. Clearly, the designers of simulation tools can no longer expect the undivided attention of users. The difficulties of deploying staff and computational resources in such a state of flux is complicated by the resource required to switch between projects.
In addition, clients often respond to successful 'what if' explorations with further curiosity (which may or may not have been anticipated in initial work proposals). To respond by rushing to the keyboard is rarely a successful strategy. There is a 'dark' side to simulation tools, which can seduce the unwary to extremes of complexity or over-simplification. This particular practice found that initial planning, ongoing supervision and quality assurance were crucial in constraining the complexity of simulation models as well as enhancing their clarity.

This collaboration facilitated the identification of key QA issues that emerged further as more of its members advance down the simulation route. In adopting a unilateral approach to simulation in a company, it is essential that:

- an individual is identified who has responsibility for overall strategic decisions in order to ensure that the aims of the company remain clearly in sight;
- someone must be responsible for the overall simulation strategy;
- to cope with an increasing simulation-based project workload, at varying design stages, simulation tools may require improved documentation, archiving and retrieval procedures in order to minimise time required to 'get up to speed' as they switch between projects; and

- initial planning, ongoing supervision and quality assurance are crucial to a successful outcome.

As a simulation-based enterprise adopting new tools, this company faced the need for intensive re-training and the risk of lost income during the changeover. Moreover, they ran the risk of having to reduce workload (while developing new skills) at a time when they were naturally expanding. By observing their work practices and developing an achievable training programme assisted by the availability of support on-demand, potential bottlenecks and barriers relating to time lost when procedures do not exist, were addressed. Because of existing expertise, the potential impact of these issues had not been considered as they had the impression that they knew what they were doing.

4.4.2 Simulation procedures

The application of simulation to support design decision-making requires a quality assured procedure for application that can be implmented effectively in practice. And the underlying reasons for adopting QA procedures are fundamental to good design practice. As defined within the CIBSE Applications Manual AM 11 (CIBSE 1998a), essentially, the purpose is to:

- instil confidence in clients that the work is undertaken to a consistency high standard;
- estimate the time and cost of consultancy and ensure the achievement of these targets;
- improve coordination between members of the building simulation team;

– ensure that the simulation work is addressing the needs of the client, ensure the simulations are accurate, introduce consistency into the implementation of simulations;
– enable new work to capitalise on previous projects;
– enable previously archived projects to be resurrected and understood;
– identify training and recruitment needs.

The *'how to'* aspects of creating, testing and proving of a computer model are often the most time consuming part of the process, and the time and resources dedicated to this early stage must be balanced with the level of detail within the model itself. However, an appropriate level of detail in documenting the development of the model is also essential for providing clarity in respect of what assumptions have been made and why, in order to allow the model to be re-visted at a later date if necessary.

A key problem highlighted amongst users in industry, is the difficulty of maintaining an audit trail beyond the base case model. As the simulation process progresses, and numerous new design scenarios are being tested, the information stored can become outdated unless a rigorous audit trail is maintained. Typical issues that this would affect are changes to:
– air change rates;
– glazing types and areas, opening schedules;
– occupancy, equipment, lighting heat gains;
– heating and cooling controls;
– infiltration, ventilation levels;

- supply air temps; and
- lighting controls.

Novice and experienced users alike find it an onerous task to track all of the changes made to the original model as it evolves. Indeed, it is often the case that once the base case model is created and archived, rather than working through a logical course of simulations there is a temptation to try to change too many variables at once rather than tracking changes individually and recording results as the design is developed. (McElroy *et al* 2003), highlighted the fact someone must be responsible for the overall simulation strategy. Whether or not this person is directly involved in the simulation process may be irrelevant, what is important is that someone is responsible for the primary strategic decisions regarding simulation scenarios and are able to direct the simulation user so that the objectives of the simulation remain clear.

Accordingly, project notes should be continually updated during the evolution of the model and the building design. The aim is to ensure that post-completion, a model could be resurrected by someone not involved in creating and testing the original model. This may seem obvious, but is difficult to manage in practice – usually due to timescale pressures that result in model changes without documentation, or in a failure to record a key step in the process. In the development of such procedures, consideration should therefore be given to the following items (CIBSE 1998b):

- documentation of the methodology and procedures used to generate and evolve the model;
- detailing of assumptions built into the model;

- ensuring that logical naming conventions are used within databases, model and zone descriptions, environmental control systems, etc., in the event that the model may be re-visited by another designer;

- use of clear directory and file naming conventions to clarify projects with multiple iterations/ parametric variations;
- documented procedures for integrating changes, (e.g. in composition or operational characteristics);
- sign-off, 'pack-up' and archiving procedures.

The time required to extract and understand simulation outputs and results in terms of design performance predictions should not be underestimated. Insufficient time invested in analysis and interpretation can contribute to misinterpretation of results and a failure to spot errors. It is recommended that businesses embarking on a simulation-based design approach develop and invoke a series of customised checks, supplemented by critical professional judgement, as suggested previously in this thesis, e.g.:

- are results as expected, plausible?
- do changes in model give expected change in predictions?
- is the magnitude of annual energy consumption similar to that derived from a steady state calculation or best practice guides, (Carbon Trust 2008(a)).
- how do results compare with similar projects?

The procedures are summarised in *Table 4.1*, (McElroy *et al* 2007). This work is ongoing and now forms the basis of a Beginner's Guide to simulation (Hand 2009).

Table 4.1: Simulation procedures

Step	Typical decision
Identify issues to be addressed and simulation objectives. Translate to simulation approach, and agree required output format and key indices required to judge performance – Client, Design Team, IBPSA staff.	Is project a 'one off' assessment? Is it a parametric or an interactive exploration? Are explicit assessments of issues such as external shading and natural ventilation required – will these require dynamic analysis or are approximations adequate?
Abstract the essence of the design and develop model at a level of detail appropriate to the focus of the study.	Is it necessary to describe the whole design or is a portion of the building representative enough to allow results to be scaled up? How much geometric detail is required?
Organise problem files and documentation and proceed with simulations – this reduces the risk of not archiving at the end of the process.	Which databases are appropriate and do modifications need to be made for this project? Are there regular patterns of occupancy and equipment use? What naming conventions are appropriate for file recovery purposes in future?
Run initial simulation and calibrate model to instil confidence in all parties.	Are predicted internal temperatures as expected? Examine impact of heat gains and losses in terms of time lags to test fabric assumptions.
After simulating, results must be interpreted, performance assessed, reports written and presented to the client.	Can the tool's native reporting facilities be used or should results be passed to an external package for statistical analysis?

The following case study outlines the approach taken by one company that took a very structured and measured approach to the integration of simulation. The process was time and labour intensive, but has delivered a robust procedure that is not dependent on the company retaining particular personnel, which was an early concern in this small engineering practice.

Case study: Development of a procedure for the application of simulation in a small engineering company

This case study involved the integration over the last eight years, of advanced simulation into a small but ambitious environmental engineering company, achieved with support through the STD mechanism.

The first stage involved the company agreeing to send two design staff members to attend training courses on the simulation packages initially identified as best meeting the company's needs. Following this, the company sent senior managers on a similar training course in order that they could appreciate the potential of the technology and so that they could better support less experienced staff through the application of their engineering knowledge to the simulation outputs: e.g. to help test the plausibility of results and whether or not changes in the model give the expected changes in predictions. This was run in parallel with the delivery of project specific support, both in-house and on the premises of SESG.

The company specialises in environmental solutions that minimise use of traditional mechanical systems and which focus on a 'whole building' approach. The use of simulation within the practice has therefore focused on projects where strategies such as natural ventilation and daylighting work hand-in-hand with the building form and fabric. Simulation is seen as essential in developing the design on these projects, representing the only available means of analysis that allows the practice to meet client needs and deliver leading edge design solutions.

Although the complexities of a full thermal simulation may not be considered necessary by some, the ultimate intention in this case is to develop a procedure for the integration of simulation in order that it can be offered as a primary design tool to every client.

The appropriateness of this will depend on project type and time constraints, and the company recognises that this route will not always be applicable.

The company has identified the following as being of critical importance, to ensure that simulation does not adversely affect the design process or the economics adversely:

- in order to avoid being side-tracked by the power of the simulation tool, the objectives of the exercise must be clearly defined, and parameters agreed;
- novice users must accept their limitations and allow expertise to develop. In this case, vital support was provided by experienced senior managers and by the researcher;
- quality assurance procedures ensure that the novice modeller can build confidence to ensure that the building performance is analysed according to appropriate criteria;
- ongoing support is essential to ensure a successful deployment and associated staff training ensures that development of skills continues.

The experience of this small practice acknowledges the need for appropriate training and subsequent support in deploying simulation. It also recognises that if support is available, results in which the team can be confident can be obtained quicker and better than by using traditional methods, thus saving the company money through reduced design development. The skills attained will allow the practice to offer clients access to leading edge technology to analyse innovative designs effectively.

The key barriers addressed in this company were in the main related to time and costs:

- support to minimise the impact of the a steep learning curve, thus reducing the timescales required to develop the necessary skills; and

– support in building the necessary resource requirement.

The removal of these barriers and the fact that the company bought the loaned equipment in order to avoid having to go through the set-up procedure again, left the company free to explore things it could only guess at before, but for other small practices they offer the following cautionary note:

> "*The main cost in making this commitment is not hardware or software, but staff training time. For a small practice, the initial start-up cost in terms of staff time is considerable. The company set out to develop its business with skills based on adopting free software, customised to suit its needs. However, it was soon discovered that for this company, the time involved in this approach outweighed the perceived cost benefits. In the end they invested in a proprietary commercial tool, despite the considerable up-front cost, and estimate that this was equivalent to a young engineer's salary for a year, based on capital outlay, formal training and time lost in moving from the old to the new methods. Without support, however, they estimate that the cost could double.*"

4.4.3 Performance assessment methods

In support of QA a Performance Assessment Method or PAM can further support use in design practice by directing the user's line of inquiry. The contribution of this research work to the development of PAMs for use in practice is not the development of the PAM itself, but in identifying industry's needs in respect of PAMs and feeding back to tool developers to inform the development of PAMs by observing the processes specialists and practitioners went through during both phases of this research, and by acting as conduit between industry and researchers allowing information to flow in two directions.

Table 4.2 Clarke (2001) outlines the stages involved in a simulation and although developed as part of the ESPr (ESRU 2009) system, and initially focusing on thermodynamic modelling, the approach is generic, and could be adapted and applied as part of any environmental modelling process, and attributed in accordance with the user's requirements from thermodynamic to lighting to the embedding of renewable technologies (Clarke *et al* 2000). The action required at each stage is <u>underlined</u> and the knowledge required to implement this is shown in *italics,* thus providing experience and inexperience modelers alike with a clear indication of the information required and highlighting where a greater understanding of the issues may be required before proceeding to the next stage. Such a PAM can be attributed with alternative knowledge instances depending on the user's viewpoint, the application topic(s) and the program's capabilities.

Table 4.2 – A generic PAM for building simulation

Stage	**Activity**
1	<u>Establish a computer representation</u> corresponding to a *base case design*.
2	<u>Calibrate this model</u> using *reliable techniques.*
3	<u>Locate representative boundary conditions</u> of *appropriate severity.*
4	<u>Undertake integrated simulations</u> using *suitable applications.*
5	<u>Express multivariate performance</u> in terms of <u>suitable *criteria.*</u>
6	<u>Identify problem areas</u> as a function of *criteria acceptability.*
7	<u>Analyse simulation results</u> to identify *cause of problems.*
8	<u>Postulate remedies</u> by associating problem cause with *appropriate design options.*
9	For each postulate, <u>establish a reference model</u> to a *justifiable level of resolution.*
10	<u>Iterate from step 4</u> until the overall performance is *satisfactory.*
11	<u>Repeat from step 3</u> to establish replicability for other *weather conditions* (where

applicable).

Case study: Development of a PAM within a medium sized engineering company

In order to help facilitate simulation management in practice, specific research was undertaken with one member company has resulted in the development of a specific Performance Assessment Method that encompasses a series of Modelling Assessment Procedures (MAPs) as a means of recording standard input information and assumptions required during the simulation process. The role of the author was to advise on the approach taken, based on past experiences and to document the process for wider dissemination. Figure 4.5 outlines the structure of MAPs, which require the recording of data in a pre-defined format in order to make simulation information more accessible to any member of the design team, and to maintain an audit trail (McElroy *et al* 2003). The information thus stored is explanatory text, design notes, assumptions, etc. and, in addition, includes data reading directly from the simulation input files. The issue of the potential for discrepancy between model data and stored model documentation was identified from the outset.

Figure 4.5: Modelling Assessment Procedure.

In the context of this particular project, the associated QA system relates to two key areas: issues relating to the model semantic (ensuring that models represent the design intent) and simulation management procedures. The procedure developed incorporated detailed documentation in order to ensure model transparency but also to minimise the risk of discrepancy between different user/ client perceptions of the design/ modelling intent. Modelling procedures therefore cover all possible design decisions and assumptions, data sources, etc. The extent of the documentation required is a crucial issue within a commercial environment, and although this will vary, depending on the nature of the project, the procedures should not impede the design process and that they do not become an additional barrier to establishing simulation within industry. This is constantly under review as simulation is integrated into the company's existing archival and intranet systems. The following section introduces MAPs in more detail.

Recording data in pre-defined forms has assisted multiple users on the same project by making simulation information more transparent and accessible by any member of the design team during the simulation process. And, as the company uses more than one simulation program, it is recognised that the framework should be holistic, ensuring accuracy of model inputs by only accepting and storing transactions that preserve existing input formats, i.e. unaltered. This is already possible for some, but not yet all, of the programs used and is seen as a key ongoing issue. The data thus stored can be viewed in its raw state by an expert user, but is mapped to a user-friendly format within the appropriate MAP for client/ non-expert examination.

As outlined earlier in this section, model preparation for non-experts is a time-intensive and non-trivial task. The intention was that MAPs would enable the design team to consider any simulation decisions, assumptions and data sources in advance of beginning the process. The benefit of the adopted philosophy is that any MAPs can be viewed, via an intranet facility by all members of the design team, whether in lead or support offices, and subsequently reviewed and amended as and when necessary.

This lack of guidance or advice on hierarchy regarding the important features of a building model can compound the problem. The need to establish and record the priorities of the simulation exercise in order that a model can be developed at an appropriate level of detail in recognised within the system and the MAPs ‘force’ experienced engineers, with little or no experience in simulation, to consider the nature of their requests in terms of the question to be answered, thus giving the modeller greater guidance. Experience from this particular project and more widely through

SESG technology deployment indicates that engineers frequently request simulation without any real consideration as to the nature of the problem, or indeed what the simulation is expected to prove or disprove. By introducing a mechanism that forces such requests to be better considered with respect to purpose, and specifics regarding areas of concern, it is envisaged that simulation users will become better able to direct their time efficiently and effectively.

Using an intranet system, MAPs can be completed on-line by those initiating a project. They are thus immediately accessible and information can be queried by support office staff and simulation users alike. As such, a succinct, process for problem definition will be developed which can only benefit the model construction stage that follows.

Model construction

Once the problem is clearly defined, and only when model geometry has been carefully planned, should model construction fully commence. In order for model construction to progress, many decisions have to be made relating to construction materials, internal heat gains (occupants, lighting and equipment), heating, cooling, control and ventilation strategies. At this stage, in the context of a live building project such information may be, but often is not, available. As a result, much of the required simulation input can be based on the identification of possible uncertainties and their subsequent translation into learned assumptions. The benefits of rigour in documenting modelling assumptions has been the subject of extensive research (Hand 1999). An understanding of what data to record and not record is critical to success. In practice, however, it is often the case that information regarding data input is at worst held only in the head of the simulation user, (based on their own preconceptions) or, at best consists of randomly recorded sketches and/or data assumptions drafted on pieces of paper, which are inevitably mislaid during the simulation process. This is in conflict with the reality of the complex nature of the buildings under examination.

At present there are few quality control systems in existence that allow the simulation user to ensure the relevance and accuracy of their inputs (Donn 1999). More importantly, if data inputs are not accessible it is impossible for a user to grasp their relevance to the simulation project. Figure 4.6 shows a prototype network MAP transformation of an air flow network data file. It provides a visual cue to an engineer by providing a diagrammatic representation of the location of air flow pathways in a multi-storey building, stored in a format outside of the simulation to be accessible to other engineers in the same company working on the same project. It is not at this stage deemed suitable for use by other design team members, such as architects, but could be developed for this purpose if desired. Such MAPs provide a mechanism to allow the initial simulation user or model creator to document the entire project, from simulation assumptions and design decisions to data files such as this. Via the intranet archival facility, this information is made available to all those concerned, although only one person will have ultimate management control over each aspect of the project (e.g. simulation manager/ design manager, etc.).

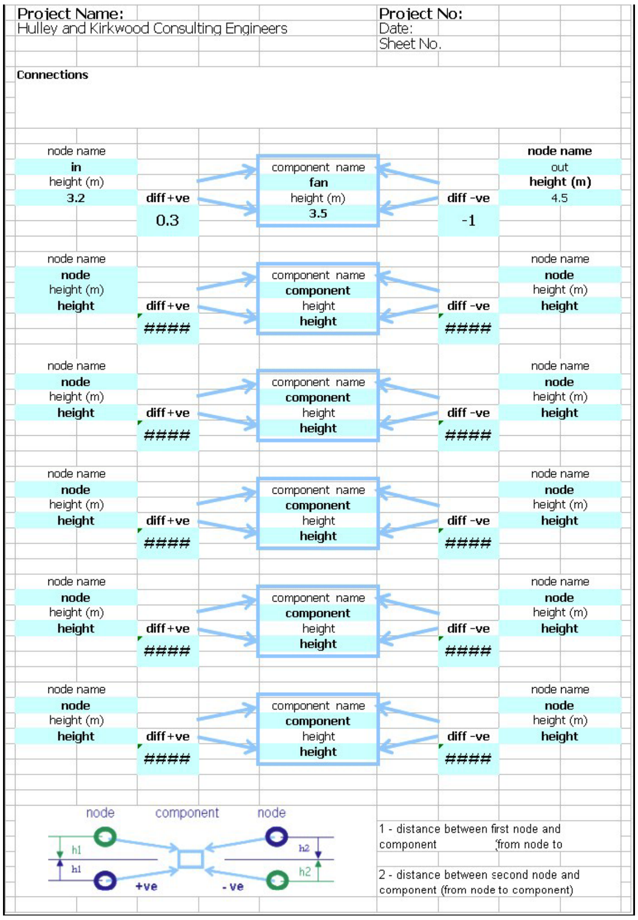

Figure 4.6: Prototype networks MAP.

Two additional benefits also arise from completing MAPs in this way. Firstly, any initial simulation assumptions can later be compared with the final design/ installation and secondly, the MAPs can be printed and compiled in a report to issue to the client for approval before simulation begins.

Simulation

As outlined above, the ability to maintain an audit trail once the simulation process has begun is a key problem for commercial users, indeed, much of the data stored within the Problem Definition and Model Construction MAPs relates to the initial or base case. This remains a problem within the MAPs, as the number of new design scenarios tested begins to increase, the information stored in the MAPs can easily become outdated unless a rigorous audit trail is maintained – failsafe solutions remain an issue to be addressed. Figure 4.7 illustrates the structure in place within the MAPs to track model development in respect of issues from air change rates, glazing types/areas, occupancy, equipment, lighting, heating and cooling issues, controls, ventilation levels, supply air temperature, etc.

As discussed above, it is often the case that once the base case model is created there is no distinct route or set of logical simulation scenarios, resulting in a temptation to change a number of variables simultaneously, and this impedes the ability to track the impact of changes individually as the design is developed. This study helped to highlight the importance of appointing one person to take in overall responsibility for managing the process with full responsibility for primary, strategic design decision making, as simulation is only one part of the process. As discussed previously, this person need not be directly involved in the simulation process, as long as they are able to direct the modeller so that the objectives of the exercise remain in focus.

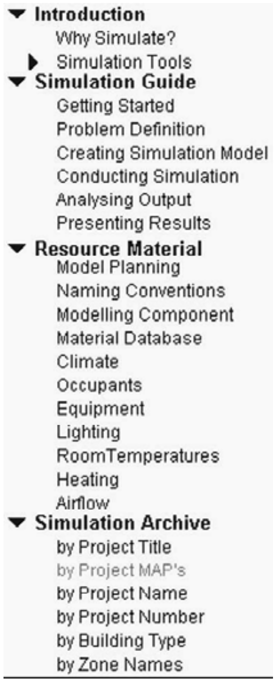

Figure 4.7: Audit trail.

It should be borne in mind that early results may not be as expected, leading to a new plan of action. MAPs can accommodate and document such outcomes, although an ongoing issue for modellers is how frequently information should be recorded. Due to the iterative nature of simulation, it may be appropriate to allow some stages to go undocumented as the model is evolving. The only problem with this is in ensuring that sufficient data is stored to allow landmark events and changes to be understood by anyone re-visiting the project.

If simulation is to be of real benefit to the professions, it is vital that archival, retrieval and storage procedures such as the one discussed here become as user friendly as possible, thus encouraging users to archive models at various stages, and provide adequate documentation. Some simulation programs already have in-built reporting facilities that detail the input data for a project model and this can provide an ideal source of information against which to benchmark these procedures. However, retrieval and understanding of the content of 'old' project data can be problematic with the passage of time. MAPs could be generated and viewed remotely and this should in time provide a company with a valuable resource of past simulation models and assumptions that users can learn from. This would overcome the current lack of performance guidelines for simulating buildings, with growing simulation archives establishing a basis for understanding the recommendations of simulation results.

Output reporting

Simulation allows designers to gain an insight into the future reality at the design stage (McElroy & Clarke 2001). As the outputs from simulation can have a significant impact on the design of a building, there is a need at some stage in every simulation process for someone with expert knowledge to assist with interpreting of simulation results. Even expert simulators often find it difficult to see beyond what they want or expect to see in terms of results. There is no simple solution to this problem and while it is important that methods for informing clients improve, developing presentation formats suitable for non-expert digestion is a non-trivial task (Soebarto & Williamson 1999). All of this highlights the problems associated with relying on a 'solution' based on the creation of 'intelligent front ends' and simplified interfaces – if the user does not fully understand the question, or the process, how can he or she fully interpret the output/ simulation results?

Performance assessment methods and MAPs could lead to an agreed method of standardising the way in which simulation results are reported to a variety of audiences, from engineer/architect to building user/client (Figure 4.8). However, the information contained in such reports would have to be tailored to suit the client, and depending on the type of study undertaken, the same results from multiple tools or integrated simulations could be collated in a variety of ways for different audiences. As suggested previously, such integrated performance views would allow comparisons of similar projects allowing clients to develop a better understanding of the processes and to become more confident about questioning simulation results.

The experience of the particular company involved in this exercise with SESG, suggests that this may result in two standard types of report for different clients:

1. Technical Reports, documenting full sets of simulation results and supporting literature for thorough examination by expert users; and
2. Recommendations Reports, typically for general client issue, and providing a brief summary of simulation results and recommendations.

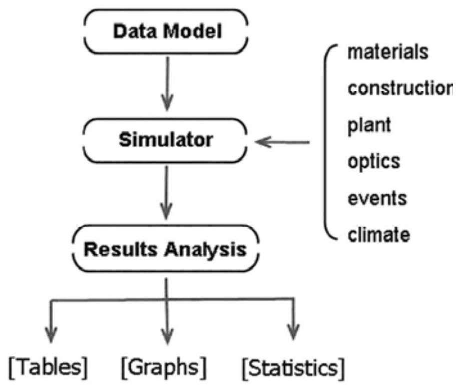

Figure 4.8: Simulation results analysis.

MAPs have the added facility of being transferable from the simulation database into typical word processing format to facilitate reporting. The technical report would allow projects of a similar nature to be compared and would assist with Quality Assurance.

Discussion

If the deployment of energy and environmental simulation is to increase within industry, it will lean heavily on the effectiveness of establishing efficient simulation management systems. Initial planning and ongoing supervision will help ensure that companies can successfully control the overall simulation strategy.

Even at the time of writing in 2009, in the case of many simulation tools, typically, system configuration does not facilitate checking of input and output data within a simulation model with regard to illogical or inaccurate data. This makes it difficult to 'get up to speed' with simulation projects initiated by someone else, resulting in a reluctance to get involved in someone else's project. Therefore, the development of transparent documentation procedures in simulation will play a pivotal role in guaranteeing the future of simulation modelling in industry. MAPs are seen as a positive step to removing some of the 'mystery' associated with simulation data input and in addition as a management system to compliment the ever-improving documentation, archiving and retrieval procedures of current simulation tools. It is not envisaged that this will detract from the need for an expert to oversee the overall simulation strategy, but should enable users to step in and out of any simulation with far greater ease than is currently the case. One concern that both academic and industrial users alike are keen to avoid is the duplication of data input as this would be detrimental to the overall efficiency of the process.

If professionals do not understand the simulation process they cannot easily use simulation results to inform their design. With this in mind the anticipated benefits of Modelling Assessment Procedures are threefold in that it they:

- will inform professionals new to simulation of the required information to initiate a energy model;
- will ensure that other members of the design team can view input data and results at all times, and can query them as appropriate; and
- can be used as a reference to cross-check data input into a simulation model serving as a tool to ensure that simulation models are consistent and accurate.

This is illustrated by Figure 4.9.

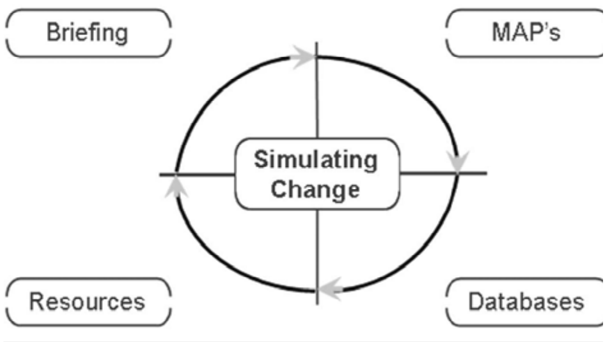

Figure 4.9: The proposed process.

4.4.5 Integrated performance view

Modelling assessment procedures (MAPs) deal largely with the information storage archival and retrieval aspects of performance assessment methods. What to do with the 'results' or outputs of a simulations exercise is another issue altogether, and has not yet been the focus of this thesis. However, as simulation moves mainstream and demands in terms of input and ease of use grow in respect of interfaces, integration, data transfer and the associated QA, on the output side, the issue of how to display and evaluate the outputs is key to the future if integrated performance assessment is to become embedded in practice. Traditionally, results for thermal studies were displayed graphically and for lighting simulations using pictorial displays for example. But as the demand for integrated performance assessment has grown, and the number of criteria to be compared increases in range and scope, to include not only the traditional thermal and daylight analyses, but also integration of passive and active renewable energy systems, acoustics and wider sustainability issues such as embodied energy impacts and environmental pollution, cross comparison of one design hypothesis against another becomes more onerous. One approach, which has been developed (initially as part of a major European project (Daylight Europe 1996)) and successfully trialed with simulation users, is the Integrated Performance View or IPV (Clarke 2001).

To enable the Step 5 activity outlined in table 4.2, the concept of an Integrated Performance View (IPV) was adopted. As depicted in Figure 4.10, an IPV can bring together the results for different aspects of performance such as seasonal fuel use, environmental emissions, thermal/visual comfort, daylight utilisation, risk of condensation, renewable energy contribution and the like, all of which may have been generated by different simulation tools, but brought together here in one place. By comparing IPVs as a design evolves, the trade-offs inherent in the design process may be made explicit and quantified.

The IPV is not program specific, and makes it possible to bring together the results from different aspects of a modelling exercise in an integrated manner. In terms of achieving the ultimate goal of a fully integrated approach to simulation in design practice, the IPV fully supports co-operative working across the design disciplines, and furthermore, provides a mechanism whereby professional viewpoints from across the design team can be presented simultaneously and an assessment made of the impact of one design change on other factors or to test one hypothesis against another. It is theoretically possible for an IPV to be generated automatically, however at this point in time,

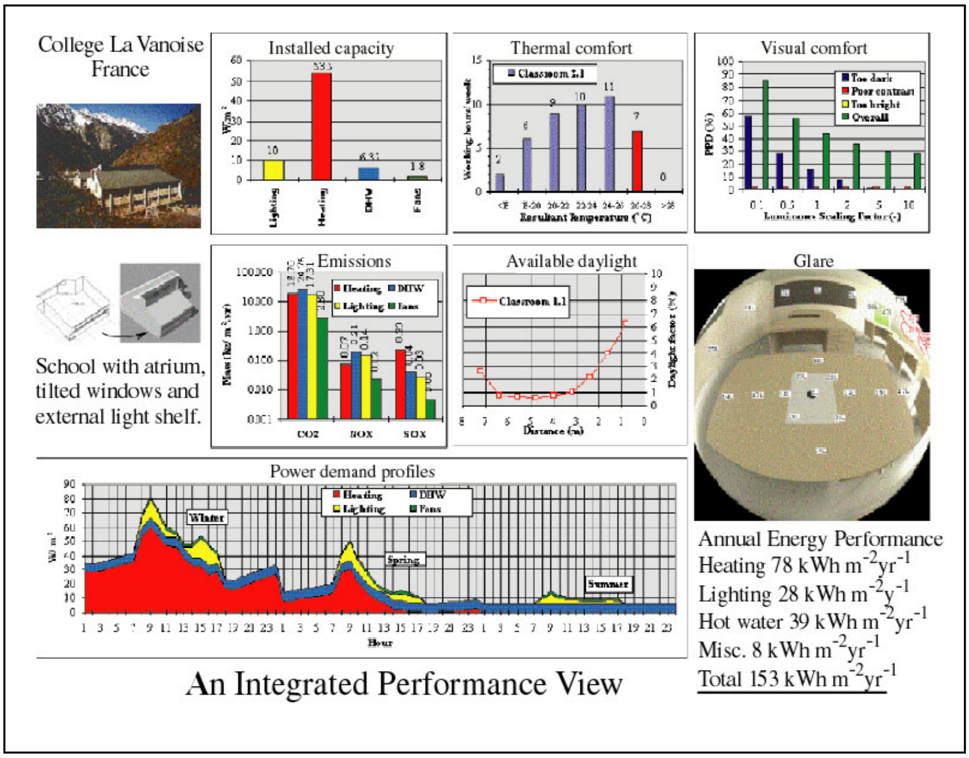

Figure 4.10 Integrated Performance View

depending on the tools being employed, it may be necessary to import data from models not fully integrated into the process, which re-introduces the risk of error. Notwithstanding, the continued development and mainstreaming of this work will theoretically in future allow designers from different disciplines and in different locations to work interactively in the pursuit of more sustainable design solutions in a manner which was not possible in the past.

The contents of an IPV could, at the time of the research in 2003, be generated from a preset list of options within the ESP-r simulation system. However, through the research this issue of what makes useful content for different audiences was explored. For example, graphs and summary lists of predicted energy usage while suitable for digestion by engineers might not suit architects who often respond better to visual outputs. Similarly while engineers might look for lighting information in lux levels or candelas per square metre, architects might better appreciate visual representations plus daylight factors, none of which may be appreciated by a lay client. A key role of the research in this phase was thus to feedback to tool developers advice on how best to interpret and present results depending on the audience.

It is anticipated that in future IPVs will be developed to include animated and interactive materials in order to better guide a wider audience of building clients and users. This is elaborated in section 4.5.3.

The research contribution with regard to IPVs is not in the development of the concept but in researching the most appropriate content of IPVs for practitioner and client use. Prior to the advent of integrated tools practitioners were already recognising the need to compare and contrast results from different modelling assessment programs – e.g. lighting and thermal, impact on energy consumption of renewable integration and risk of glare associated with daylight use, for example.

Observations of the industry in phases 1 and 2 supported the academic perception of a need for mechanisms to bring together results in one place in the absence of integrated tools at the time. Most importantly, industry dialogue and focus group observations gave rise to the need to display information in a meaningful way, and informed tool developers as to what was important to practitioners at large. The appropriate contents for an IPV will depend very much on the audience. And despite the power of simulation, it was observed that the professions preferred to see information in familiar formats and using traditional methods of measurement as this gave rise to greater confidence in outputs – e.g. for benchmarking: Normalised Performance Indicators (NPI) in kWh/m^2, energy consumption in buildings: kWh, emissions: CO_2 or Carbon, or comfort measured using the conventional steady state Predicted Mean Vote (PMV) or Predicted Percentage Dissatisfied (PPD) systems as mentioned above.

Architects might want to see images, engineers numbers and graphs, and a client wants to relate something that he or she reflects their building in appearance before trusting any figures.

What will be right for one customer will not suit an other. However, almost unilaterally if IPVs for design variants can provide something that gives a clear visual comparison in graphic or visualisation terms, backed up by appropriate numbers to reflect the impacts of design changes, the message can generally be articulated across the board. An excellent case in point being the series of simulations undertaken to demonstrate aggressive energy reduction and renewable energy integration on the Lighthouse. (Not in thesis). A series of IPVs graphically illustrates the progressive impacts of aggressive energy demand reduction methods combined with passive and active building integrated renewables over summer, winter and mid season scenarios.

Case study: Use of IPVs to demonstrate demand reductionn and renewable energy potential on the Lighhouse Building

The regeneration of the Lighthouse building designed by Charles Rennie Mackintosh was the City of Glasgow's flagship project in response to being nominated as UK City of Architecture and Design 1999. The project was one of the last studies undertaken within phase 1 of the research and the design team wanted to examine demand reduction and renewable energy opportunities on one part of the building as a demonstration of city-wide potential for building integrated renewables. The study provided an early opportunity to explore the use of multiple simulation tools including ESP-r and MERIT (ESRU 2009) and brought together the results of thermal, daylighting and renewable energy simulations in one place on an IPV for the first time.

The case study describes the sympathetic integration of passive and active renewable technologies in the refurbishment of this historically important building in the city centre and elaborates on the use of IPVs to assist decision making with regard to the systems finally adopted on this building as a live demonstration of urban scale renewable energy use and the wider implications in terms of integration of such technologies in cities.

A unique feature of the Lighthouse building was the intention to use the building as a demonstration of the potential for use of renewables on an urban scale by incorporating renewable energy technologies within the structure. A specially configured portion of the building was selected to serve as a testbed to showcase state of the art technologies which demonstrate the integration of passive and active renewable energy components.

A detailed analysis of the potential cumulative benefits of the following 3 passive and 2 active renewable technologies was undertaken using ESP-r and MERIT:

advanced glazings (low-e, prismatic & switchable)

daylight utilisation and luminaire control

transparent insulation with integral shading

photovoltaic cells (stand alone and facade integrated with heat recovery)

roof mounted, ducted wind turbines

The investigation utilised the ESP-r building simulation system to explore the opportunities to use passive renewable technologies to minimise heat and power demand and active renewable technologies to meet residual requirements. A base case model was generated and the above technologies were added cumulatively with the aim of establishing the lowest, practical energy demands and then sizing the components to meet that demand as far as possible.

The findings overall are demonstrated in figures 4.11, 4.12 and 4.13. Figure 4.11 demonstrated the base case model, with double glazing and no lighting control. The heating energy demands are modest and confined to winter and mid season, and the lighting demands (also low) track these. Figure 4.12 demonstrates the impact on energy demand of various passive measures with aggressive demand reduction. A key point to note is the flattening out of the heating and lighting demands effected by efficient lighting and responsive heating in addition to advanced glazing, a Transparent Insulation Material (TIM) wall and lighting controls. The outcomes demonstrated in figure 4.13 were that the passive technologies in combination with critical control, could reduce the demand profiles to an extent where the active technologies - in the form of photovoltaic components and ducted wind turbines - could quantitatively approach this demand. The study outcome confirmed niche opportunities for small scale deployment of renewables in the City, emphasising the importance of securing a balance between demand reduction and energy supply. Most importantly from the research point of view, the profiles selected for inclusion on the IPV demonstrated that it was possible to get the message across to even a lay client with the minimum of description.

QuickTime™ and a
decompressor
are needed to see this picture.

Figure 4.11 IPV for Lighthouse Base Case Model

QuickTime™ and a
decompressor
are needed to see this picture.

Figure 4.12 IPV for Lighthouse Base Case Model plus demand reduction and passive solar components

QuickTime™ and a
decompressor
are needed to see this picture.

Figure 4.13 IPV for Lighthouse Base Case Model plus demand reduction and passive solar components, with ducted wind turbines, and PV electrical and hybrid.

4.4.5 Benchmarking

As suggested previously, designers lack confidence to use new approaches if they have no concept of what outcome to expect. Benchmarks provide a means to judge the integrated performance of a building against others in the same class. They also allow users to scrutinise the impacts of new program releases.

Building on the work undertaken in the early phases of the research, supported use of simulation in practice has facilitated the collation of a repository of models of specific building designs that typify certain ranges, and this is generating model performance data, normalised by floor area, weather, etc. It is envisaged that feedback from this could be used to develop integrated performance benchmarks based on application of theory to live projects. This is based on the range of criteria that would typically be used to characterise building performance: energy efficiency, comfort, air quality, environmental impact, renewable energy utilisation, and so on.

These benchmarks could provide a mechanism to compare the integrated performance of a building with others of a similar type of thermal characteristic within the same type (Carbon Trust 2008(a)). This work is ongoing, but is being facilitated by the introduction of the Energy Performance of Buildings Directive, which will ultimately drive the requirement to match theoretical analysis predictions with monitored data. Through the research, work with particular early adopters of the technology has given rise to the development of specific, in-house approaches to integrated performance benchmarking, which is transforming businesses. The following case study typifies the approach.

Case study: Use of simulation to develop standardised models to assist benchmarking

This project involved the building of in-house simulation assessment capabilities for a large design and build contractor, specialising in health care facilities. The aim in this case was to support fine-tuning of the design of environmental control systems. In particular, this company's designers held the belief that they could deliver designs that would maintain patient comfort while at the same time reducing environmental system complexity and initial costs, but they were fighting against the *"....but, this-is-how-we-always-do-it..."*, view of their sub-contractors.

The support provided in this case allowed engineering staff to compare and contrast the performance of alternative designs and, furthermore helped them to demonstrate that there was no negative impact on comfort for patients as a result of adopting alternative approaches. In the process, the staff involved gained confidence in use of the simulation tool employed. The project involved the development of 'virtual wards' and the simulation processes demonstrated not only the response that the engineering staff had expected, but also gave them the enhancement of an ability to fine-tune the model and/ or to review related performance issues interactively. This provided them with indicators of the work-flow/ timescale issues that they could expect once staff were proficient in use of the tools.

Furthermore, focused support led to the development of design ideas that could be applied generically in typical patient rooms, resulting in considerable savings in initial costs and on long-term maintenance. Bearing in mind the fact that this is a contracting company that is used to operating within tight timescales, it would have been understandable if they had decided that they could not make available the time resources required to acquire the skills necessary to develop an in-house simulation capability. It would also have been easy to opt to contract-out the work, having taken the initial steps necessary to understand the process. However, the longterm view was taken that if they took the time now, they could gain a competitive edge and timescale advantages through building up a set of standard design against which new work could be benchmarked. Thus, having realised the benefits, the company seized the opportunity, and with the support of management and SESG throughout the process the staff were afforded the time to develop skills to a high enough level to take them beyond some of the key barriers:

- the timescales required to develop the necessary skills;
- lack of trust in the accuracy of models and
- risk of misinterpretation of results.

4.5 Monitoring progress

Throughout the six years of research reported in this phase, the initiative was closely monitored in order to refine the technology transfer mechanisms in place. This provided an opportunity to measure whether or not it was achieving its aims, and to make adjustments if required. To supplement the project documentation and publications, round table Focus Group discussions became an important element in steering the research in accordance with perceived industry needs.

Within the wider Scottish context, which has over 8,000 registered architects and 800 building services engineers, the monitored activities gave rise to several significant outcomes, each relating to a specific performance target established at the outset of the research. These are summarised below:

- membership had grown to 32 companies, with around 300 individual members and a wider mailing list of over 500 people registered to receive information – indicating a general interest in the concept of in-house simulation activity and a willingness to engage, evident in two sectors – small '*niche*' practices and medium - large construction companies;
- most member companies had adopted the new technology and reported an expansion in the scope and depth of the work they are undertaking – indicating an appetite from the client base, and the perception of added value;
- over 1900 individuals from over 140 Small to Medium size Enterprise (SME) companies (defined as companies of less than 250 employees worldwide), attended seminars, while around 530 of these received software training inputs – indicating a positive trend for the future, albeit perhaps driven by impending legislation. Training sessions ranged in attendance from around 10 per session for issues relating to non-mainstream issues such as indoor air quality and life cycle assessment to nearer 50 for climate change abatement and Building Regulations issues;
- 235 supported technology deployments were completed in over 30 SME companies, each involving in-house assistance with the application of modelling and simulation within live projects – this was an extremely positive result, and on further investigation, revealed that in companies where more than one STD took place, a significant number of staff had been trained on a number of simulation tools;
- 71 new jobs were created, (compared with a target of 66) mostly through the employment of new graduates possessing refined modelling skills and 85 jobs have

been safeguarded (compared with a target of 35) by the promotion of modelling activity (over 30% of these include women and people under the age of 25) – indicating the potential for simulation to create new jobs for graduates with these skills, which might help address the timescale and up-skilling barriers by introducing a new breed of engineer to both engineering and architecture practices. It also links back to discussion in Chapter 1 of a need for engineers with softer but broader skills who appreciate the design and engineering elements of buildings and the call by Egan for greater co-operation across the team and beyond;

- companies had released staff to pursue higher degrees as a result of technology uptake - raising an interesting proposition in terms of breaking down barriers – not by forcing re-training, but by the gradual integration of a new discipline within the team.;
- 7 companies had published papers at international (5) and national (2) conferences on the results from their simulation work or the impact of simulation on their business – this was a positive step in breaking down barriers between academics and design practice. Many academics believe that they design tools for industry use, but there had been little evidence of successful industry adoption thus far;
- an investment of the order of £3.4m by member companies in R&D and innovation;
- an increase in local software sales amounting to almost £1million.

The final two achievements are significant considering the construction industry in Scotland has traditionally lower levels of investment in R&D and innovation than other sectors, and because the perceived hardware and software costs associated with adopting a simulation approach had until now presented a significant barrier to industry.

At the outset of the research, several mechanisms were adopted to transfer the technology into practice. In addition to traditional approaches (seminars, workshops and newsletters) more novel approaches were employed in the form of internet-based advice and in-house supported technology deployments.

Appendix 8 tabulates the events and supporting activities undertaken over the period recorded and demonstrates that the regular seminar/ training/ supported technology deployment cycle has been well supported throughout the project.

A typical seminar would have three or four speakers with expertise in the topic being addressed. A key aspect of this is that the speakers are not limited to the developers and sellers of software tools, but also encompassed the users community. For example a seminar on building regulations included speakers from the Scottish Government, BRE and the University of Strathclyde. The aim of a seminar is to introduce a topic and illuminate how simulation tools can be used to address the issues.

Traditionally, seminars have been followed by training in specific software tools. This has allowed those present at the seminar to develop new skills within a fully supported academic environment. For example, following on from the building regulations seminar training, was a series of events focused on tools that offer a regulations compliance checking capability.

The final element in the monthly cycle was the Supported Technology Deployment (STD), as introduced in section 2.2.1 and elaborated in 4.3.1. At the project's outset several barriers were identified to the use of simulation, including the availability of suitable hardware/ software and application know-how. These barriers are addressed by providing a company with an appropriately configured computer and an application specialist. Typically, an activity would focus on a key aspect of a design, for example natural ventilation or the integration of a renewable energy technology. The loan computer was left with the company for an appropriate period of time to enable practitioners to explore more design options than would be possible if the work was outsourced, and as and when requested, on-site support from a specialist was made available.

4.5.1 Objectives and targets

The ongoing monitoring evaluated the extent to which the initiative was achieving the objectives set out in the project proposal:

- the establishment and maintenance of an industry network, including its size, composition, membership and growth rate and income generated;
- the traditional services provided to the network, such as the delivery of new information services; the training of staff in new and novel technologies;
- novel services provided - provision of support for software applications on live projects through training and STDs;
- scope and impact of wider dissemination activities;
- knowledge transfer activities: the effectiveness with which integrated simulation has been transferred to the industry and the wider network including job creation and student placement;
- support for changes to internal working practices of the member organisations to

facilitate the adoption of new technologies through STD activity and ongoing support beyond this.

It also considered the wider impacts of the work on dissemination of new knowledge, processes and technologies and facilitating the two-way transfer of knowledge between research institutions and industry through:

- the effectiveness placement of graduates with simulation skills in industry including the number and type of new jobs created;
- improving the competitiveness of Scotland's SMEs involved in the delivery of the built environment;
- the effect on economic development, arising from enhancing the capacity of SMEs through raising their R&D capabilities, enabling them to offer an integrated performance assessment service, and encouraging supply chain development;
- the benefits within Scotland from reduced energy and environmental impact, improved indoor/outdoor air quality, human comfort and health, and use of local resources, arising from more informed decision making including explicit appraisal of options at the design stage;
- impact on the supply chain and demand for innovative products;
- spin-off job creation brought about by the increased demand for innovative products, such as renewable energy technologies and smart controls for building services;
- the stimulation of enhanced R&D with the design and construction sector;
- raising awareness in Scotland of environmentally sustainable (clean) processes and products within and beyond the construction sector;
- development of strategic alliances between industry and academic/ professional

organisations and

- assisting its members to address the challenge posed by sustainable development, and the requirements of the EU Energy Performance of Buildings Directive (EPBD) (EU 2003).

The monitoring exercise also compared the actual outputs of the project against the levels forecast by considering:

- the number of new and existing SMEs engaged in the project (target - 35 SMEs engaged);
- the number and impact of business network events (target - 72 major events, 20 SMEs per event 2004/ no target number of delegates set from 2005);
- the number of instances of advice provided (target - 135 Supported Technology Deployments);
- the extent of sales of new software (target - £1.1m in sales of licences);
- new products introduced (target 28 – 2004 – 2008 only);
- new jobs created (target 66);
- jobs protected (target 30 actual 85 2004 – 2008 only);
- increased investment in innovation (target - £2m 2004 – 2008);
- increase in sales in participating companies (target £2.59);
- the savings in carbon dioxide emissions (target 24,000 tonnes per annum (2002 – 2004 only) actual approx 50,000 per annum).

The outcomes of the monitoring and impacts of activities are outlined in section 4.5.2.

4.5.2 Impact of activity on embedding simulation in practice

At the end of 2008, 32 organisations were members of the network, comprising 12 consulting engineering practices, 6 architectural practices, 3 computer simulation companies, 4 local authorities, and 7 others, including one building contractor and an insulation manufacturer. 23 of these are SMEs with fewer than 250 employees including some very small organisations with fewer than 10 employees. There had been a healthy turnover of members over the previous 8 years and membership has not remained static. Each member organisation pays a subscription of £500 per year for membership, representing a total income of £16,000 per annum.

In addition to subscribing members, there was an informal network of around 500 individuals who were kept informed of activities of the initiative via email invitations to the network events and copies of the newsletter. The aim was always that the group should not be rigid in supporting only those who pay membership fees, but to also be open to individual participation in respect of the traditional dissemination events – newsletters, seminars, general training and workshops.

Traditional mechanisms – seminars, workshops and training

A series of monthly themed seminars, workshops and training events ran throughout the year. Monthly training courses, typically related to these themes. About twenty topics were identified on the basis of general interest, novel technologies (e.g. the hydrogen economy), and 'need to know' (e.g. Building Regulations) as follows.

– *energy efficiency, indoor air quality, design integration, building regulations,* *lighting systems, life cycle assessment, renewable energy systems, fire engineering, climate change, sustainable cities, small scale renewables, HVAC and controls, electrical services, outdoor air quality, acoustics, value engineering, international developments.*

The number of delegates attending events and a summary table is included in Appendix 8. At the time of writing (September 2008):

- 50 seminars had been run, attended by a total of around 1900 delegates, with 'need to know' events such as Building Regulation changes and EPBD attracting upwards of 100 delegates annually, and generating an average of 24 delegates per event;
- 15 workshops and discussion groups had been run, attended by a total of 140 delegates, and with an average of 9 delegates per workshop;
- 40 training courses had been run on various software packages, including ESP-r, TAS, FLUENT, Cymap, Radiance, MERIT, Envest, Eco-tect, TRNSYS and SBEM (BRE 2005). These attracted 535 delegates, at an average of 14 delegates per course. The trainers include in-house research staff as well as representatives from software suppliers. It is interesting to note that, while initially it was more junior staff who attended training sessions, gradually, managers have taken part in order to see the functional capability of the tools available, so that they can actively guide the process in-house.

Since 2006, 6 training courses run in conjunction with BRE on SBEM to meet EPBD requirements have attracted on average 20 – 25 attendees per event.

Training was offered on various software packages concerned with, for example, heat flows, lighting, and computational fluid dynamics, and provided by both in-house research staff and software vendors. Delegates comprise individuals from SMEs, but also from larger companies, local authorities, utilities, government and the universities.

Feedback was overwhelmingly positive with events described as well-structured, well-presented, relevant, useful, informative, insightful, and enjoyable. As a result of running these events for practitioners, it was discovered that some topics (such as current and forthcoming legislation) are of greater interest than others, and also that there is a limit on the frequency with which practitioners will attend events, 5 workshops and 6 training courses had to be cancelled or postponed, leading to a review of the programme of events.

The research findings confirmed sufficient ongoing industry uptake to recommend continuing with these traditional support mechanisms as a means of supporting integration of modelling in practice. Moreover, the events provided a useful forum for discussion with industry colleagues, tool vendors and researchers on mechanisms that would ease the way towards a simulation-based approach in future.

Novel mechanisms - beyond conventional training

235 STDs were undertaken over the six years of operation, with around 50 different organisations. All but a few, such as Atkins Global, Glasgow City Council and the Scottish Government, were SMEs. The number undertaken substantially exceeded the target of 135. A list of supported technology deployments is included in Appendix 8

and is implicit in Appendix 9 recorded here as *Instances of advice and support to SMEs*. The range of topics covered by STDs include the following:

- lighting– glare assessment, daylight factor calculations, daylight quality assessment;
- computational fluid dynamic assessment internally and externally - wind flows around buildings, fume dispersal around buildings, thermal bridging and mould growth,
- thermal analysis - heating and cooling systems, thermal comfort, renewable energy, modelling of photovoltaic façades;
- renewable energy integration;
- scenario planning for energy efficient refurbishment.

This validated the aforementioned assertion that the range of areas of interest from practitioners was expanding and confirmed the need for integrated tools to address a variety of issues at once.

In addition to delivering benefits to the companies receiving support, it was reported that supported technology deployments could provide these companies with the appropriate language to provide valuable feedback to vendors concerning issues that arise when their software applications are used in practice, due to the support of the specialist staff with their broad experience of various software packages combined with the practical experience of design team members. Thus, in effect, the bringing together of these two groups facilitated the 'unravelling' of some of the barriers to tool deployment in practice by revealing to the tool specialists and design teams alike the difference between academic theory and the demands of design practice.

Dissemination

The newsletters and conference presentations reported above in section 4.2.2 have provided an opportunity for the research to engage with the international building simulation research community and to reach out to other mainstream practitioners. Further, by reporting on the research outcomes to fellow practitioners at industry conferences, the group has illustrated to potential new users some of the practical issues that arise as well as the anticipated benefits of tool use in practice. These activities demonstrate clear evidence of a growth in confidence in the design community with respect to both participation in simulation activity, engagement with academia, and useful dialogue with the simulation profession generally. The increasing depth of the line of enquiry now taken by practitioners was illustrated by a demand for more in-depth knowledge. In order to log and share enquiries relating to more complex support, the newsletters stored and pre-empted this activity through a series of frequently asked questions (FAQs) in order that the responses could be shared more widely.

Knowledge transfer between research and industry

At the time of writing it was reported that, 12 of the member firms were using ESP-r, 11 were using IES software, 7 were using Radiance, 4 using Cymap, 3 using Hevacomp, 2 were using Fluent, 2 MERIT and 3 Tas. Reports varied as to the extent to which the organisations actually exploited these new technologies. Some attended workshops and training courses primarily to learn about the latest developments and keep up with the current state of the art, but reported that they would probably continue to use specialists to undertake work on their behalf – albeit better informed than before.

However, by this point in the research, evidence was emerging of an enthusiasm for adopting the technology as a full-blown in-house activity. This was demonstrated in three ways:

- three member companies engaged in the government funded Knowledge Transfer Partnership (KTP) (KTP 2005) scheme to undertake joint industry-academic research into computer simulation working with the University, and subsequently employed the research assistant to embed the new technologies within their organisation and offer them commercially. (This is described further below as part of the report on the Focus Group discussion.)
- investment by members in 53 new software licences at a capital cost around £18,000 each, totaling £950,000. (The actual figure is complicated by the fact that during the funding period, some 'open source' software was made available to users at no cost).

In addition, there was increased uptake of places by post-graduate students on modelling related masters courses:

- Energy Systems and Environment – with 20 - 30 students;
- Sustainable Development of the Urban Environment – with 5 – 10 students; and
- Integrated Building Design – with around 10 students.

Students on these courses arrive with a mixed range of backgrounds and the courses themselves introduce them to a range of tools, including ESP, IES software, and TAS. As a result of their education and training, those with interest and aptitude acquire skills in simulation modelling which make them highly sought after.

Three engineering consultancies used the KTP scheme supported by the research mechanism to embed the new tools into their working practices. The majority of members have adopted the new technologies to a greater or lesser extent, while the remaining handful attend workshops and training largely in order to keep up with the state of the art, (rather than actively using these tools in practice).

Job creation and student placement

It was anticipated that the initiative would contribute to the placement of graduates possessing simulation skills, thus creating employment opportunities. Moreover, as these jobs would in the main be office-based and reliant on electronic communication, it can be argued that this could create greater opportunities for the employment of engineers who do not have English as a first language, or are women and/ or from ethnic minorities and/ or differently-abled. According to the research, by the end of July 2008, 71 jobs had been created. Of these around 25% are for women, 30% for people under 25; and most relate to environmental activity and or creation of jobs for people with modelling skills. These figures illustrate that the initiative has been extremely successful in creating employment and placing young graduates with such skills, and moreover, that the uptake of simulation in-house by over 30 organisations has been facilitated by integration of new design team members with skills that complement those available traditionally.

4.5.3 Impact on the built environment sector in Scotland - focus group discussion

In order to explore some of the figures recorded in the monitoring in more detail, focus groups were arranged to gather feedback from members throughout both project phases. The findings and their impact on the research are outlined below.

The reports of the focus groups are amalgamated below, except where changes in practice or activity were identified.

Job creation and placement

Feedback from one member of the group (A) explained that this firm had used the KTP scheme to work with two graduates (KTP Associates) while moving simulation into practice. One associate had been engaged in a project concerned with standards of service to clients, the other with the place of simulation in practice, including quality assurance issues. Both KTP Associates have subsequently been employed full time by the company.

The need for simulation within this company had expanded, particularly when the firm took on major hospital work and this necessitated moving from a ‘research-based’ tool (ESP-r) to commercial software from Tas and IES. ESPr is still used for CFD analysis. This company is keen to up-skill engineers to use simulation modelling rather than using dedicated modellers. They have recently taken on half a dozen building design engineers on placement from Strathclyde and are training them in-house with SESG support. In addition, some these engineers have obtained accreditation as Low Carbon Consultants via CIBSE (2008) and are also training as BREEAM Assessors through BRE (BRE 2008).

This company's experience indicates a perceived benefit in investing in a new type of graduate to support the necessary up-skilling of existing staff when adopting new technologies. The company now has a highly skilled modelling and sustainability literate workforce and has set up a new skill base within the practice to promote the new technologies through in-house CPD.

One issue identified as a result of taking on this major hospital project was the need for tools that could address acoustic quality in buildings as part of a wider package of comfort issues relating to air movement, air quality, thermal and lighting quality – all of which are major issues in acute hospital wards and in ancillary spaces such as operating theatres. Although mentioned as a passing remark at this juncture, the issue of linking the wider aspects of spatial perception, including aural and olfactory issues has been the subject of recent research (Prazeres 2006) facilitated through the SESG membership, in the exploration of animated, three dimensional and manipulable integrated performance views in the first instance. And although it may appear that the desire for an integrated, interactive, (and intelligent?) performance view is merely an indulgence, in the view of those charged with demonstrating concepts and ideas beyond the design team, it may well be that there is good reason to pursue this goal. Indeed this would be an important step in terms of communicating ideas to the wider community such as non technical clients and building users given the recent advances in GIS mapping and virtual reality technologies, that allow users to experience the building model three dimensionally by virtue of an interactive headset 'immersion'. The whole issue of human interaction with the environment in respect of all the senses, is not a new area of research and is well documented, e.g. by Gibson (1966) in his book *The Senses Considered as Perceptual*

Systems. However, the exploration of the senses beyond the visual in the simulation field is novel at this point in time. Others working in the field of adaptive control and adaptive opportunity include Nicol (2008).

Another member (B) explained that his architectural practice had also used the KTP scheme to work with two KTP Associates – one on the use of simulation in practice, the other on sustainability issues. Both Associates had gained PhDs and had been subsequently taken on by the company. This supported the view that in their drive to embed the technology in practice, companies were now exploring new territory in respect of increasing investment in R&D in order to facilitate new ways of working, and that the cost was being borne up-front in order that the necessary up-skilling could take place within a minimum timeframe.

A third member (C) reported that he had been involved in the delivery of Masters training at the University and confirmed that 3 of his post-graduate students, had gone on to gain employment in firms offering simulation as a matter of routine. Similarly, this case evidenced the fact that even in a small company, the value of releasing a young staff member to further study in order to maintain a competitive edge was recognised.

Group member (D) reported that they had recently adopted ESP-r and had continued to develop skills across the office in Glasgow. This was significant, as although regarded as one of the most flexible and powerful systems available, ESP-r is traditionally seen by the industry as primarily a research tool, which requires high level of skill to operate usefully in the real-time design world. The enthusiasm in this practice demonstrated a determination to get to grips with a technology that could answer any question that they might ask in future, however, they did not under-estimate the level of support that would be required to up-skill to this level.

Member (E) said that his firm used the SESG for training staff in a variety of tools, in order to gain insights from within a non-biased, independent support infrastructure. The firm has one dedicated person in the Glasgow, London and Leeds offices and they generally use commercial packages – IES and Tas.

The latest member to join the group (F), reported that the company is using ESP-r to look at energy conservation possibilities in cruise liners. For them ESP-r as open source code is ideal because of the possibility of customising it for this unusual project type. A key benefit for them has been in marketing. It is very difficult to win commissions from cruise liner companies, but his company has promoted their capacity to offer simulation modelling as an specific selling point and has won consultancy work as a direct result. This has enabled them to take on a dedicated energy modeler, in an industry that is notoriously energy profligate.

All participants confirmed that in their experience the initiative was creating jobs and assisting in the placement of graduates with simulation skills.

While the focus group provides what is essentially anecdotal evidence from a limited number of member organisations, it supports the achievements of the research in terms of developing a support mechanism (the STD) for tool use in practice, creating a forum for discussion on key simulation topics (advocacy groups) embedding simulation in practice job creation and the placement of graduates skilled in simulation.

Economic benefit of increased investment in innovation and R&D

Group member (B) reported that engagement with the initiative has stimulated greater interest in R&D within his practice, and that the company now perceived itself to be at the forefront of the new technology. They are involved in PFI/ PPP projects where simulation expertise had helped to win them commissions. Member (A) reported in 2004 that his engineering practice wanted to build simulation into the company's standard portfolio and to use it to look for new business opportunities. He provided the example of 5 PFI/ PPP secondary schools in which they had been involved at the early design stages and where they were able to use their simulation expertise to assess the possibilities for natural ventilation in deep classrooms. In a later group meeting, his colleague reported that he believed that their clients interests in simulation related primarily to meeting regulations and suggested that the forthcoming EPBD and Energy Performance Certificates will place new expectations on clients. He pointed out that as there is no requirement for an overheating check in the Building Regulations in Scotland, there is less often a need to make a thermal model of a building, although he concurred with other industry representatives on that occasion that compared with the past, when energy consumption was seen as the key factor, now, overheating and comfort issues tend to drive clients' requirements for simulation, stating that:

> *"….offering simulation modelling is no longer just a matter of better public relations, it is increasingly expected by clients and is particularly important for international commissions such as those in hot climates."*

This represented an interesting shift in perception regarding the value of modelling over the period of the research.

Member (G) in 2008 reported that simulation expertise had enabled his company to give more scientific estimates of future energy use compared with traditional rules of thumb. Member (H) reported that as a result of acquiring the software, they had increased their fee income and won new work. They had even obtained consultancy work purely to undertake simulation appraisals. He believed that the training element has been important for the firm, although they had not ruled out the possibility of adopting commercial software for EBPD compliance in the future – as both IES and Hevacomp have SBEM accreditation. He went on to explain that part of the motivation for this relates to regulations that have to be met, such as the imposition by some local authorities of a certain percentage of the energy in the building has to be generated by renewable sources on site. Comfort is also a driver for the use of simulation. And as clients don't want inefficient buildings, there is also a public relations dimension attached to the use of simulation in practice. Member (E) confirmed that within his company, the capacity to use these tools has enabled them to maintain their market position. He reported that interest in low energy design can go beyond simply public relations. He has two projects where a commercial tenant has asked him to assess costs and benefits of various renewable energy technologies over a 20-year payback period. He added that:

> *"….the rise in capital cost has contributed to an increase in fees, although one client was willing to pay extra fees for the extra service to be provided."*

Thus, evidence gathered from the field was beginning to suggest that simulation was now, in many cases expected as part of the service offered by design engineers, and that clients were beginning to appreciate the added value, with some paying for the service. There was also evidence that the range and scope of uses was continuing to expand, beyond the traditional energy performance issues, to comfort and controls. And in the longer term, simulation would be necessary to meet the requirements of UK and EU legislation.

Impact on buildings in Scotland

When asked about the impact of their new skills on buildings in Scotland, the focus group delegates gave examples of where this had occurred. These included better exploitation of natural lighting arising from computer simulation of sunlight and shadows in high-rise housing and better understanding of visual impact, both of which were important in negotiating with planners. Design teams themselves had gained new insights, and sometimes surprises, from computer simulation. More generally, the firms reported that they are increasingly engaging with the issues of environmental design and sustainability, with benefits to the environment and quality of life. Other associated observations for the research are listed below.

Group member (A) reported that in his opinion visualisation software was valuable for marketing new buildings to clients and for making presentations that convinced planners. With regard to the earlier phase of the research, this echoes the impression reported 10 years before in the development of a methodology for simulation model building – whereby it was reported that clients expected to see something that looked like the building – even if its content was meaningless (see *section 3.5*) Refurbishment and renovations also benefited from simulation, citing an example of a 21 storey building that his firm was working on with a developer, and where computer simulation of sunlight and shadows was valuable to ensure that the expected quality of light was retained in the development and to convince the planners. Simulation is being deployed to each of the firm's 9 UK offices.

Group member (B) agreed with the original proposition that simulation could bring benefits to architecture, occupant comfort, and energy and environmental issues '*quicker, cheaper and better'* than conventional methods, which was as valuable to architects as it was to engineers. He reported that in his company, 3 or 4 architects were interested in environmental design and sustainability issues, and that knowledge of the importance of these issues was spreading throughout the firm from the Glasgow office to the other three offices (in England). During the period when he had been a KTP Associate, one of the firm's directors had become interested in sustainability issues, and this had provided an opportunity for him to report regularly to the Chairman about sustainability and the enhanced services they could now offer. This was a useful insight, as it demonstrated that the need to 'push' the technology on the industry was gradually being replaced with a willingness to engage, the 'pull' alluded to in 1998, was now beginning to happen, eight years into this phase of the research.

Member (G) reported that his firm had been using the thermal calculation tool Hevacomp, but working with the group had enabled them to thoroughly review more advanced simulation tools, with support and as a result, they had decided to become users of IES software. The firm found that simulation was a 'selling point', making it possible to show clients what was being delivered and helping them to understand the building better, for example through the visual impact of daylight. By giving the design team new insights, simulation could on occasion give even the design team a surprise, and again this was a benefit. While initially they had been extremely cautious, the firm now uses computer simulation more often than not, and had introduced a policy in both their Glasgow and Edinburgh offices to use simulation where appropriate. This was a significant step forward for a traditional, small- medium-sized building services company, with a traditional approach to services design and further research on this reveled that there was now a growing trend among practices of this type and size.

Stimulus to increase demand for innovative products

The focus groups also discussed whether or not up-take of simulation, (for example through its ability to increase the accuracy with which building performance could be predicted), would increase demand for innovative products, such as advanced glazing materials, smart controls and renewable energy technologies. The general view was that demand for such advanced products arose from enlightened clients who wanted their buildings to be greener. However, it was agreed that simulation could build on this in that, through simulation it was possible to assess the benefits more accurately for products such as high specification glazing, which would increase demand. And, although the consulting engineers, for example, were mostly concerned with mechanical services in buildings, simulation provided the opportunity to understand better the contribution to building performance of the building fabric. The notion of being able to present the impacts on performance of such technologies within an integrated performance view was seen as extremely valuable in terms of presenting a full picture of the benefits or otherwise of novel technologies and the knock-on effects on other design issues to clients. However, the fact that these could be demonstrated at this juncture, but not yet produced with ease and automatically for the majority of software tools, was cited as an ongoing frustration, as this made it more difficult to sell good ideas or to dissuade clients from making ill-judged decisions. Somehow, presenting everything in one place made a more convincing argument.

Similarly, both engineers and architects in the groups had used simulation to explore possibilities of new technologies, such as the potential for using sun-pipes to increase the perception of daylight in hospital wards, for example, and although they had not proved feasible in the particular case, generally simulation was leading to better integration of such new technologies into buildings. One of those interviewed reported that they had even set up a similar in-house focus group within the firm to keep the practice up to date with the latest developments in renewable energy technologies and are currently working with manufacturers to review the technologies – simulation was valuable to this exercise as it increased the accuracy with which the benefits could be assessed. An important point raised was that while in the past, due to lack of confidence in the technology, a firm might over-design in order to build in a margin of safety, there was now an acceptance that this margin could now be reduced through the application of simulation, as the results would (theoretically) be more accurate. In terms of moving the research forward, this attitudinal change is significant in an industry that has been applying the same rules of thumb since the 1930s. In addition, other benefits such as the fact that use of simulation to assess building energy performance gains credits in BREEAM (BRE 2008) assessments, were also highlighted as reasons for making changes to include simulation as an integral part of the design process. It was remarked that if a standard set of procedures and simulation methodologies could be developed for universal use, along the same lines as the old rules of thumb, the industry would adopt these readily, particularly if endorsed by the professions, or if enshrined in regulations. However although intended as a positive statement, this did indicate a desire for user-friendly tools and suggested that the industry wanted a quick-fix solution despite all efforts to demonstrate the complexities involved and the benefits of a gradual uptake. This was in-part driven by commercial pressures.

Economic development, R&D and supply chain improvements

When the project was set-up, few of the organisations that were by now members of the group had any members of staff responsible for simulation assessment. At the time of writing, it can be reported that seventeen of the member organisations (50%) – have up-skilled to the extent that they now have staff members, and in some cases have set up new teams to allow them to offer integrated performance assessment as part of their standard service. The focus group confirmed that this has allowed them to win work that they would have been unable to undertake before. The increase in impending associated legislation could in part be the reason for this, and an increase in clients seeking to be more environmentally conscious, however, neither of these issues account for the fact that companies that would traditionally have employed tried and tested methods, or that would have been happy to engage with external intermediaries, were now not only dabbling in the technology, but embedding it in practice and freely discussing the issues and benefits with rival organisations. This is claimed as a direct result of almost 20 years of supported engagement and associated research.

Through the advocacy work and focus groups, this research work has also helped in the building of local supply chains for innovative products, and has brought together companies with mutual interests and assisted members of the network to work with companies that they had not previously had the opportunity or the inclination with which to engage.

These insights demonstrate that the initiative has contributed to economic development by enhancing the R&D capacities of energy sector companies, enabling them to offer an integrated performance assessment service, and encouraged supply chain development, as predicted in the original project proposal.

The benefits within Scotland from better-designed buildings

The original proposal for setting up the initiative, made the claim that there would be benefits to the Scottish building stock from reduced energy and environmental impact of buildings, improved air quality and better comfort, wellbeing and health.

A clear example of the advancement of growing confidence within the industry in the technology was reported in a paper written jointly by an engineering consultancy and SESG (Macdonald *et al* 2003), which includes a case study of a large factory suffering from severe overheating. In this case, as a result of disparities between simulation results and measured conditions, it was discovered that nine-tenths of the ventilation fans in the factory were inoperative. In consequence, planned installation of air conditioning was deemed unnecessary, resulting in a capital cost saving of about £100,000 and annual running cost savings of 715,000 kWh, worth about £36,000 p.a. It was also found that a planned new insulated roof would need only modest insulation, saving a further £50,000. The cost of the simulation was £4,000. This may be an extreme example but it demonstrates how the industry was growing in confidence – trusting the simulation and not what appeared to be evidence in the ground. The project also highlights the importance of quality assurance and a methodology for application in practice as outlined in 3.5.

The cost/ benefit ratio in this case is spectacular, although it is doubtful that it is typical of every project where simulation is applied. However, from past experience of monitoring the outcomes of the first phase of the research between 1992-1998, predicted energy savings were estimated for every single instance of advice-giving, and revealed that the ‘80/20’ rule applied, in that, the majority of the measurable benefits arose from a relatively small number of key projects, although the vast majority of projects also delivered some benefit. It seems likely that the same trend would occur here, with most of the instances of applying simulation leading to modest but nevertheless valuable benefits, while in a small proportion of cases, the benefits are significant. Unfortunately, it was not possible to examine the impacts in all the member organisations to examine the scale of the resulting benefits in any detail. However, for the purpose of reporting, a means of calculating the savings in carbon dioxide emissions arising from its advice-giving has been devised. It is based on several assumptions:

- the floor area of an ‘average’ building project;
- the number of companies and projects supported; and
- improvement in energy use in the buildings receiving advice from ‘good practice’ levels of energy usage to ‘best practice’.

According to the calculations undertaken the work to date has resulted in Carbon dioxide savings of around 50,000 tonnes per annum. Without taking account of the impact of the potential additional impact of any consequential spread of simulation throughout the industry, cumulatively over the 9 years of operation from 1999 to 2008 these initial steps could amount to over 2.25m tonnes of CO_2 saved based on the typical fuel mix in Scotland.

Other issues

The participants were asked whether they had publicised their interest in simulation. All reported that publicity had mainly been internal, although the new skill had been added to the company portfolio on websites, and had been promoted to clients through company newsletters, etc. None of the focus group participants had made any significant attempt to promote simulation through the professional or technical press.

All the participants confirmed they had invested in simulation and gained resulting benefits. They also said that they could not have achieved what they had without the support of the initiative, nor could they do what they planned to do without it. In some cases, developers were now approaching the engineers to use simulation to explore site layouts, plot sizes, building massing, and glazing, rather than going to architects, since (with a few exceptions) architects did not have the ability to do simulation based analyses. All recognised that in order to retain major clients it was necessary to stay ahead of the game, and offering simulation was one of the ways of doing so.

While only a small sample of members of the group's business network was consulted, the evidence collected through the focus group indicates that the integrated simulation approach is being effectively transferred to members of the business network, that some are now offering an integrated performance assessment service and have invested in R&D. All of these developments reflect the aspirations set out at the commencement of the research programme. Furthermore, they illustrate that the research undertaken to date has successfully changed the landscape of building design in the way that was envisaged.

Two of the companies participating, had recently become accredited as Low Carbon Consultants (CIBSE 2008). One of these is on the threshold of training up 20 employees. And their representative believes that clients are primarily concerned with meeting regulations and the forthcoming Energy Performance Certificates (EU 2003) will place new expectations on clients. The other company already has six accredited staff. Among the specialist commissions requiring integrated simulation, Member (H) reported that his firm has used CFD for analysing smoke movement, and also for assessing heat dissipation in the Dublin Metro and London Underground.

Member (D) reported that his company is acting as technical advisers to clients (for example, a bank) and checking proposals prepared by others under the Private Finance

Initiative. PFI projects have tight performance requirements for the delivery of comfort conditions, with the rental reduced if these conditions are not met. As part of a due diligence programme, ESP-r has provided the company with the capacity to check that the specification requirements will be met in practice. However in terms of improving energy performance it can be argued that a 'looser' rather than a tighter approach to performance parameters, based on adaptive control and user intervention has greater potential to save energy. This is (as stated previously) an area of current simulation research (Nicol *et al* 2008).

In addition to the focus group, a quick survey of two other members who were unable to attend, were extremely positive about the contribution that this initiative has made to their ability to offer simulation as an integral part of the design process, and about the benefits to them as organisations resulting from the simulation support mechanism as well as the benefits for their clients and the gains to the buildings they advise on. One cited as an example, a 20,000sqm regeneration project in Edinburgh where the in-house support enabled them to achieve the best results in terms of daylighting and thermal zoning. Another drew attention to the forthcoming Energy Performance of Buildings Directive and the challenges it will pose to the design of buildings as an example of the climate of innovation to which they will have to respond by developing new expertise.

Spin-off job creation and demand for innovative products

The original proposal predicted that this initiative would bring spin-off job creation by increased demand for innovative products such as advanced coatings, smart controls for building services, and renewable energy technologies. This subject was raised with the

Focus Group as reported above who confirmed that there was spin-off job creation and gave examples.

Further examples include a housing association being advised by the group, which had decided to invest in photovoltaics, and this led to the construction of the UK's first hybrid photovoltaic roof for Partick Housing Association in Glasgow; a company that manufactures double skin facades who are in discussion about the development of algorithms to represent the façade performance; a firm of blind manufacturers which is discussing control algorithms; a firm making low cost structural and thermal insulation panels and another making ducted wind turbines.

Despite these connections with manufacturers, barriers to some sectors remain. It is still the aim that by engaging with and increasing the involvement of organisations such as the Heating and Ventilating Contractors Association (HVCA), the Construction Industry Training Board (CITB) (now Construction Skills) and other similar bodies, including more manufacturers, this initiative could be instrumental in the process of raising operatives' skills and expertise in the installation of new energy technologies.

From these views and explanations, there is evidence that this initiative has been successful in increasing demand for innovative products although, the group would like greater engagement with suppliers and manufacturers, and their associations, to help bring this about.

Enhancing R&D within the design and construction sector

This work has contributed to research and development activities among member companies and through the wider business network. This was discussed during the Focus Group, where organisations taking part confirmed that their involvement in the KTP scheme was a direct plan to engage more with R&D activities. Other companies in the network have sent their employees on post-graduate study courses. Additional evidence of the growth of interest in R&D is the authorship of the 19 conference papers whereby practitioners are increasingly reporting their engagement with R&D by a route traditionally dominated by academics.

Raising awareness in Scotland of sustainable technologies

The original project proposal envisaged that the project would raise awareness in Scotland of environmentally sustainable (clean) technologies and products within and beyond the construction sector. Renewable energy systems have been one of the monthly themes for the group's events, and several of the events addressed renewables. Many supported technology deployments relate to the integration of renewable energy technologies into buildings, helping to promote clean technologies. In addition, the initiative has contributed to presentations at various events. Involvement in the pan-European REASURE project (see Strategic Alliances below) shows it is helping to raise awareness of environmentally sustainable services.

Strategic alliances

The research has included networking with a number of international organisations. For example, the SESG operates as the Scottish representative body on the International Building Performance Simulation Association (IBPSA) and, reports its work internationally at IBPSA conferences. It also acted as a Scottish facilitator for REASURE, a European programme concerned with design and advice support to promote the use of renewable energy in buildings and has participated in the EU network ENERBUILD (now concluded) concerned with the promotion of energy efficiency in buildings, and in cluster meetings of the European network USOBUILD. The above provide mechanisms for the dissemination of this work and to date these alliances have generated a great deal of interest in the possibilities of such an initiative elsewhere in Europe.

The group has set up an alliance with BRE (BRE 2005) for the delivery of training in SBEM, iSBEM, SAP and rdSAP to facilitate up-skilling of the industry in preparation for meeting the requirements of the introduction of the Energy Performance of Buildings Directive from 2008 (EU 2003).

The group has also participated in joint events with The Chartered Institution of Building Services Engineers (CIBSE), and this also helped increase interest within the building services profession of the work of the group. Continuing Professional Development events have been run with the Scottish Ecological Design Association (SEDA), the Scottish Solar Energy Group (SSEG), the Energy Institute, the Centre for the Built Environment (CBE) and with GAIA Group. The group is also involved in an EPSRC-funded network concerned with comfort in buildings and run from Oxford Brookes University.

4.6 Why has it worked?

In summary, the STD mechanism has proven itself to be a powerful technology transfer device, largely because training is an integral part of a familiar process and is undertaken in the real time, real scale context of design practice. Following a successful STD, it is not unusual for a company to acquire the featured simulation package and send staff on related training courses. This is a key point: a serious investment in software and training is only made after the benefits of a program have been demonstrated in a commercial setting. In this way, companies are able to evaluate the appropriateness of alternative programs before making a decision to invest.

The companies showcased in the Case Studies made a commitment because they see simulation as the only way of addressing the design challenges with which they are now faced. They believed that if they did not accept this challenge now, they would be overtaken by their competitors in the future. A key message is that while machine deployment and in-house training will ease the way, they nevertheless face a transition phase, between old and new practices while still meeting day-to-day programme requirements and deadlines. It is difficult to maintain a balance that does not adversely affect productivity. This may explain why up until now, most of the associated activity has been in larger practices.

A survey of members was undertaken to ascertain the elements of the program that had enabled them to routinely use simulation. These responses fall into two categories:

4.6.1 Drivers

Commercial applications of simulation are geared towards increasing the service available to clients, and staying competitive as a company. For example, in enabling better design through a computational approach a company can predict reduced energy consumption in final buildings or reduced environmental impact of a building. Key drivers include:

- International protocols: *e.g.* Kyoto and Local agenda 21. These increase the political drive for a sustainable, low carbon economy without giving detail as to how this should be achieved. In doing so there is a popular perception that good design is equivalent to low carbon/ life cycle cost.
- National legislation/ schemes: *e.g.* building regulations, EPBD, BREEAM, LEED. These drivers are more specific in their impact as there are clear pass/ fail criteria. An important aspect of many of these schemes is that there are degrees of pass, *e.g.* for the EPBD a highly energy efficient building will be A rated and a building which only satisfies the minimum regulations may only be a D rating.
- Commercial pressures: *e.g.* type of procurement, company development. In the UK there has been a move towards costing based on the life of the building for government projects. This has increased the demand for an ability to calculate annual running costs. Additionally, there has been an increased desire by companies to bring simulation work in-house, to increase value and control of the process (*i.e.* cheaper and quicker design - two of the initiative's three key aims).
- Design pressures: *e.g.* increasing complexity, new partnerships. The integration of novel features in buildings: double skin facades, building integrated renewables, etc. In combination with these new technical demands companies are increasingly working in partnership with others in the design team. This has lead to calls for

performance quantification on timescales that can only be delivered upon if the work is undertaken in-house.

Overall, these drivers have resulted in clients demanding more sustainable buildings and reduced life cycle costs, with the aim of an increased profile for their 'green' building. Counteracting this is a desire for the overall capital cost not to increase. As a result the desire by practitioners to be able to quantify building performance as early as possible in the design process has increased; thus they can make informed decisions about design changes and their impact on the overall design.

However, the use of simulation at early design stages is not risk free. There are many unknowns and although the impact of assumptions can be quantified it is not routinely applied. Instead the practitioner relies on their knowledge and new barriers to uptake are encountered (Hobbs *et al* 2003):

- increased risk of liability to the practice;
- unfamiliar working methods;
- lack of fundamental knowledge; and
- perceived increase in workload.

These ongoing barriers are being tackled by improvements in training, management and software developments, however, without ongoing support for design decision making, in respect of the most appropriate assumptions to make and how then to apply these to simulation outputs, to the benefit of the evolution of the design, the risk of mis-application remains. This is a key issue for the future of research in this area on the basis of the original assertion: that simulation can produce results ‘quicker, cheaper and better’ than conventional design methods.

4.6.2 Advances

To successfully employ simulation tools, advances are required in several areas including a skilled user-base and software applicability for design work. Not surprisingly, many companies reported a desire to adopt computational tools for in-house application, but have been discouraged by the interfaces to these tools. This resulted in a need to sub-contract simulation to specialists not only to undertake the modeling work, but also to interpret the output, translating the results into meaningful information for the design team. However with increasing numbers of graduates emerging from courses where the opportunity exists to develop simulation skills, there now exists a good platform from which to tackle the issues related to users.

In the UK the TCS/KTP (Teaching Company Scheme/ Knowledge Transfer Programme) (KTP 2005) has been instrumental in allowing companies to bridge the gap between academia and practice. Several member companies have used TCS/ KTP associates as a mechanism to enable them to embed simulation into their existing procedures, augmented by improving training, and the development and uptake of QA mechanisms across the company - i.e. the use of simulation in a company has not been the sole responsibility of an engineer (usually a recent graduate). In one company the use of simulation was curtailed when the only trained user left to work at a competitor’s office.

Detailed QA/ training schemes have been adopted by member companies, and include steps questioning the need for simulation, the specification of what design question should be quantified and feedback to ensure that the model was fit for purpose. To minimise the impact QA has on model development time (as is often the case with QA procedures) companies have examined methods by which reporting can be automatically generated. This has included engaging developers to make changes to the reporting available from their tools and creating bespoke tools. The latter option is often required as companies use a variety of software systems depending on the problem to be solved, but want a standard reporting mechanism. For example, this was achieved by using spreadsheets in one company (McElroy *et al* 2003) and a bespoke interface in another (Hobbs *et al* 2003).

Finally, simulation software provides detailed information on the problem analysed, but often does not directly answer the design question. For example, can an office be naturally ventilated? To answer this the practitioner will have to assume openable areas and then test this hypothesis with say an air flow network. This will then tell them the air change rate: but this varies over time and what will be the air distribution within the space? So how does the practitioner respond to the simulation output: sometimes it may work, and sometimes it will not? Practitioners have started to be able to translate this information into their designs. They will often ask for a CFD run or two to characterise how the air is distributed in a space, and will be able to make judgments on what the risk of failure is. As such there is still a gap between the academic simulation tool development and their practical deployment. This relates back to the issue of ***Abstraction*** as discussed in sections 2.2.3 and 3.5.4 and this remains an important ongoing issue.

4.7 New initiatives

Despite the successes of the research work reported here, without a support mechanism, there are still significant barriers to the widespread adoption of simulation tools for environmentally responsible building design. The old barriers may have to an extent receded as a result of developing a support mechanism, but the issue of sustaining this activity is unresolved.

The following sections introduce how the research might progress by focusing on the issues that will impact most on the continued uptake by energy sector businesses.

4.7.1 Facilitating software research and development

Emerging areas of interest from the group that might direct future research include but are not restricted to the following.

- The European Energy Performance of Buildings Directive. This legislation has been enacted since May 2007 and will require urban energy performance to be predicted, monitored and reviewed on a regular basis. This is a signal development because, for the first time, the requirement to model will be enshrined in law.
- Low carbon technologies ranging from conventional devices such as heat recovery schemes through novel systems such as combined heat and power and air/ ground source heat pumps.
- Solar air collectors for ventilation pre-heat and the alleviation of surface condensation and mould growth.

- Demand reduction in its various forms from increased equipment efficiency to demand side management using remote switching technologies.
- Citizen health and wellbeing with the focus on tools for the study of environmental emissions, air quality, human comfort and evacuation.

Furthermore, in association with third party organisations, the initiative is facilitating software research and development by providing access to its membership to assist with the testing of new versions of software.

For example, one project mobilised the membership to help with developments on the LT Method (Baker 2001), to expand the tool's use from the UK to Europe. SESG hosted three workshops, initially to demonstrate the tool to potential users and subsequently to support testing it on live projects. Through these activities, the tool designer was provided with access to consultants who were able to test proposed refinements in terms of interface friendliness and technical capability. As the users are experienced designers, they were able to compare the test results with accepted industry benchmarks for the same building types. This activity is being repeated for other tool/user combinations.

It is often quoted that two different users of the same tool will get two different answers to the same problem. If the industry is to progress unsupported, this issue must be tackled in order that practitioners can have the confidence to use and defend the results from simulation tools. Perhaps, with the introduction of CIBSE Technical Memorandum TM33, Tests for Software Verification and Accreditation (CIBSE 2006) and the emerging CEN standards (CEN 1996), there will be readily available facilities to provide industry with the wherewithal to achieve this in the near future.

4.7.2 Government intervention

After many years of trying to encourage designers to adopt a computational approach to design, with little government support – other than in the form of 'pilot' projects, we find ourselves experiencing an onslaught of legislative interventions that will force us down this route. This has both positive and negative implications for the construction industry worldwide.

There is concern is that in many cases this is being implemented without adequate consulation with the industry and without a full understanding of the implications for small and medium sized companies in particular. In attempting to meet our environmental obligations in Europe for example, we are experiencing difficulties due to the fact that neither the industry nor the available tools are ready to meet the challenge. Implementation of the EPBD was due in January 2006, but was delayed in Scotland until January 2009, as too few organisations posessed the in-house skills required for compliance checking. Given that the simulation industry in the UK is fairly mature, it is recognised that in the wrong hands, simulation can be used to provide 'answers' that mean little in terms of delivery. In other words, without buy-in and a degree of understanding from the whole team, technology can be as much a hinderance as an asset in the delivery of a more sustainable environment. And, while the new legislation is, on the one hand seriously challenging those practitioners who currently do not use building performance simulation software, on the other it is starting to provoke a greater sense of ownership in terms of delivering a building as part of a ‘process’ rather than as a ‘product’, within more enlightened practices, and is thus encouraging wider adoption of the technology within those design teams. Notwithsanding this, one of the biggest concerns at the moment is the gulf between theory and practice.

In the UK, using SBEM which is being developed by the BRE, designers will be required to test their ‘Actual’ building against a ‘Notional’ and ‘Target’ building, in terms of meeting Building Regulation performance targets based on theoretical building usage patterns. This tool will be available as a stand alone or as a plug-in to the main commercial packages in the UK. It is not a substitute for simulation and is purely seen as a Building Regulation compliance checker, and therefore does not provide a target energy consumption figure, purely a comparison with the ‘Target’.

As part of the EPBD, in some countries, legislation is already being drawn up that will require ongoing monitoring after a period of occupation, to monitor energy performance and presumably to compare actual with theoretical and then to trouble-shoot any problem areas that this throws up. However, currently there is no obligation to do this, with some countries opting in and others not at the moment. So in other words the regulations will require theoretical integrated energy performance criteria to be set, but this will not (necessarily) be tested in practice.

Those imposing such legislation must put in place the necessary mechanisms to ensure effective and measurable results. If governments are serious about reducing the global environmental impact of buildings, they must therefore commit to two things:

- investment in training of those that are responsible for the implementation of the legislation (on the basis that poorly understood ‘input’ results in meaningless ‘output’) and
- to back up theory with monitoring in order to better quality assure the use of building energy performance assessment tools in practice, and to improve the accuracy of the tools themselves by measuring actual building performance – thus providing better building benchmarks in the long run. The issue of funding for POE is a contentious one, and one which is regularly raised by an industry seeking government support for such activity, as yet it remains unresolved.

4.8 The next steps

The research reorted to date has helped to equip the professions with the necessary skills to allow them to apply simulation tools routinely in practice. With support, over 50 practices have begun to tackle such issues as: the steep learning curve to tool proficiency; perceptions of poor ease of use; fear of the implications of user error; discontinuity between program capabilities and the scale and complexity of real buildings; demanding human and technology resource requirements; credibility of predictions; the need for specialist computing equipment and, most importantly, the lack of a supportive network. These companies are now well-placed to communicate design ideas and variants to their clients.

The requirement now is to further raise awareness within the construction community and beyond, and to facilitate delivery of more sustainable buildings by improving understanding of what this means in a language appropriate to different audiences, aiming to engender a need for performance quantification in practices that are currently reluctant to adopt the tools in-house, and to improve communication of the benefits tto a wider client and building user/community audience. The remaining key barriers relate to the fact that despite improvements in training, management and software developments, without ongoing support in respect of the most appropriate tools to select, assumptions to make and how to interpret and apply results to the benefit of design development, the risk of mis-application remains a key issue for the future.

The challenge to the building design profession may seem daunting, yet with the assistance of such initiatives as those described in this thesis, innovative practitioners have already demonstrated that over the course of the design process, effective use of early stage information allows better designs to be produced at lower cost and in a shorter timescale.

The next chapter explores what future work is needed in order to allow the industry to continue to build confidence in demonstrating the benefits of simulation to clients and the wider community of building occupants and users.

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Chapter 5 –Future Work and Conclusions

"Towards a clearer imagining of future realities." *(Hand 1998).*

Over the last 20 years or so, the potential of building simulation to assist the delivery of energy efficient, sustainable buildings has become well-recognised and the use of the technology by progressive design practices is growing, to the extent that from once being the domain of academics and specialists, these tools are now in use in most medium to large building services practices on a regular basis. This process will continue in the light of new regulations in Europe with the EPBD and worldwide, particularly in the USA with certification schemes such as LEED (LEED 2009) and ASHRAE Std 90 (ASHRAE 2009) which will require analysis of renewable and alternative energy sources for new buildings and major refurbishments. The applicability of these technologies can only be quantified through using an integrated simulation approach, with experience showing that this is best achieved in-house by design professionals. The potential power of these technologies is not in question. However, expectations vary, and practitioners need to build experience over time. As governments move to the introduction of a computational approach to building regulation compliance, the need for support for tool use in practice is becoming more evident.

Technology transfer initiatives such as those reported here, combined with simulation development work over the last 20 years have demonstrated that in the right hands, simulation can define a computational approach to design in the real world. This has brought the industry to a point where tools now exist that can allow practitioners to undertake integrated performance appraisals quicker, cheaper and better that other methods.

The sequencing of the research activity was as follows:

- encouraging the uptake of simulation in practice through provision of a support system that alleviated barriers to tool use in practice;
- developing a specialist support infrastructure and quality assurance procedures to advance this activity;
- linking of this activity with recognised research, design and development activity in order to assist government in meeting Carbon reduction and energy efficiency targets; and
- developing mechanisms, procedures and a support structure to facilitate the embedding of simulation in practice.

Over the years barriers to the use of simulation in practice have been documented by various users and researchers, these range from:

- the need for specialist computing equipment,
- through a steep learning curve,
- to fear of unrecognised data input errors and
- lack of credibility of predictions.

There also remained at the outset of the work a perception that simulation is:

- costly and slow,
- that users lack trust in outputs/simulation specialists
- in their ability to interpret results,

– a lack of support for program use in practice and

– the absence of quality assurance procedures.

Progress was also hampered by:

– a lack of recognised quality assurance procedures,

– poor interoperability between tools and

– an ongoing problem in relation to the jargon associated with the technology.

All of the above were traced back to one or more of the following issues, which continue to present barriers to routine tool use in practice:

– hardware and associated staff resources;

– user interfaces;

– problem definition;

– performance assessment;

– results analysis;

– quality assurance; and

– business integration.

The issues were not all equally weighted, and although solutions were required in all cases, some aspects could be addressed more easily than others.

Research - Phase 1

From the outset the first phase of the research from 1987 – 1998 tackled the barrier caused by a lack of confidence within the professions with regard to the need to up-skill, through an information transfer programme supported by seminars, case studies and CPD.

Access to simulation through the Energy Design Advice Scheme in phase 1 protected the professionals with whom it interacted from the other barriers by appointing experts to design teams to undertake simulations, but to an extent tackled the issues of trust between professionals, simulation experts, tools ad results; understanding the process of using if not integrating simulation and broached the need for QA ad simulation methodologies and procedures.

The issues of hardware and software costs and specialist equipment had all but disappeared by the end of the first phase of work due to the introduction of powerful PCs.

This work did not address the time or cost of training, the cost of undertaking simulations, or the steep learning curve.

Research Phase 2

Based on experience over the previous phases of the research, the greatest threats to the use of simulation in design practice centred on the following remaining barriers:

- timescales required to develop the necessary skills;
- lack of trust in the accuracy of models;
- credibility and risk of misinterpretation of results;
- the impacts of uncertainties;

– risks associated with user error: and, most importantly:

– the lack of support available to develop the necessary skills.

New barriers encountered in this phase included:

– increased risk of liability to the practice;

– unfamiliar working methods;

– lack of fundamental knowledge; and

– perceived increase in workload.

These ongoing barriers are now being tackled by improvements in training, management and software developments, however, without ongoing support for design decision making, in respect of the most appropriate assumptions to make and how then to apply these to simulation outputs, to the benefit of the evolution of the design, the risk of mis-application remains. This is a key issue for the future of research in this area on the basis of the original assertion: that simulation can produce results 'quicker, cheaper and better' than conventional design methods.

Despite the successes of the research work reported here, without a support mechanism, there are still significant barriers to the widespread adoption of simulation tools for environmentally responsible building design. The old barriers may have to an extent receded as a result of developing a support mechanism, but the issue of sustaining this activity is unresolved.

The remaining key barriers relate to the fact that despite improvements in training, management and software developments, without ongoing support in respect of the most appropriate tools to select, assumptions to make and how to interpret and apply results to the benefit of design development, the risk of mis-application remains, a key issue for the future.

Phase 2 assisted the understanding of issues such as risk/ fear of error, uncertainty, results interpretation, lack of confidence, true costs, steep learning curve, by allowing organisations a supported opportunity to test the water. It demonstrated the important role that the development of in house procedures applied to a bespoke or generic PAM or simulation methodology could play in alleviating barriers. The work did not focus on the development of PAMs but on identifying the need for assessment methods and informing development of these by observing the *ad hoc* processes simulation experts and practitioners go through by working as conduit between industry and companies – which allowed information flow in two directions.

5.1 Remaining barriers

The research reported in this thesis has demonstrated that simulation can be effectively deployed in the presence of a formal support mechanism that assists designers to turn outputs from a computational model into information that can usefully inform design decision making. However, in the absence of such a mechanism, routine use in practice remains problematic, in particular with regard to simulation and model management and the fact that the data produced will always have to be interpreted before application.

This remains a major barrier to simulation deployment on a universal scale, but also highlights the risk of mis-use as soon as ‘the support mechanism’ is removed.

With regard to the future, in order to meet the requirements of impending and existing environmental legislation there is a need for tools that support greater interoperability and which address an ever expanding range of energy and environmental issues. This is contradicted by an opposing demand for tools that are (in appearance at least) ‘easier’ to use. Training and the development of simulation skills within the design team can only go part of the way in terms of addressing these issues. This strengthens the case for continued support for the use of tools in practice in the immediate future, particularly given the fact that users can be seduced by the apparent simplicity of the interface.

As discussed previously, users need to be confident that models can be saved, recovered and modified over the life of the design process and beyond if necessary. This requires the application of rigorous simulation methodologies, QA procedures and systems that adequately support model creation, documentation, archiving and retrieval. While such systems exist in theory, the reality is less consistent due to human intervention. The level of attention to detail required to support the real needs of users, who, despite their own QA systems will continue to develop and modify designs rapidly, haphazardly and in haste, forgetting to use agreed naming conventions, returning to the model, say 6 months later, or passing the problem to a colleague or colleagues from different disciplines, etc., must not be under-estimated. There will always remain a risk that systems’ hidden, unidentified errors, will result in the perpetuation of model inaccuracies. The devil is indeed in the detail.

Ongoing barriers to universal uptake fall into two main categories and are identified as follows.

The need for support for technology transfer

– a need to continue to address the problems of uncertainty arising from both performance assessment and the design process itself;
– a need for continued research on universal validation procedures for all models in order to build confidence in users regarding accuracy;
– an ongoing need for a mechanism that will support users wishing to deploy simulation in the context of the timescales and real time pressures of design practice as the trend towards co-operative/ interdisciplinary working continues.

These issues have been explored to a greater or lesser extent within the context of this thesis and by reference to the work of others in this area. They are the subject of ongoing research, and continue to be fundamentally important to universal deployment.

The need for software development and hardware issues

– a need for tools that can support increasing levels of complexity and an increasing number of issues within one tool – and/or greater interoperability data exchange facilities that can be employed throughout the design process;
– a growing need for inter -tool and -disciplinary data transfer – to allow greater flexibility and to facilitate the integration of simulation in the design process;
– a need for ongoing development of Quality Assurance procedures (QA), Performance Assessment Methods (PAMs) that support data management and

associated audit trails/ archival and retrieval procedures to address the everyday, real time demands of the design process; and

- a need for further development of data input/ project management systems and integrated performance views (IPVs) to support more complex needs such as three dimensional spatial perception, acoustic and olfactory aspects of design and other multi-dimensional issues as outlined in section 4.5.3., in order to better explain the meaning of results to clients and other building users.

Potential solutions to the above are discussed below with reference to current trends and activities.

5.2 Barrier alleviation

Identifying solutions to the remaining barriers to integration of simulation in the design process presents a significant challenge to both tool developers and users alike. This has been the subject of considerable exploration in the past, under two main areas of interrelated research: firstly, the need for a generic, integrated model or data interchange facility that is adequately comprehensive to serve a useful purpose throughout the design process, and secondly, a need for 'intelligent interfaces', that acknowledge the complexity of buildings and at the same time support a variety of user types (from student to researcher to practitioner and from novice to expert). Investigation of the interactions between building fabric, environmental systems, and controls and the relationships between these and the performance criteria set by the design team to address legislative requirements from the earliest design stages to commissioning the final building necessitates:

- facilitating communication between designers and tools/ applications;
- addressing the potential impact of uncertainty and risk;
- ongoing software validation issues – in particular in relation to the increasing use of simulation for regulation compliance;
- supporting appropriate audit trails, archival and retrieval systems;
- providing appropriate, integrated feedback to facilitate model development;
- the ability to deal with dialogue between tools/ applications and models;

and, as we move forward towards an era of design team co-operation, including a government drive for enhanced, wider engagement:

- taking on board the impacts of building users and their understanding of the built environment; and
- user needs, aspirations and perceptions of buildings and their surroundings.

As long ago as the 1980s the potential of integrated simulation tools to deliver more energy efficient, environmentally conscious buildings was already well recognised. However, despite the availability of a number of dependable energy simulation tools, there were major barriers associated with transferring these technologies into design practice, mainly because of shortcomings in user interfaces. These shortcomings arose from a conflict between the necessity for the model to be powerful, comprehensive and accurate enough to adequately represent the complexity of the real world while, at the same time, being simple, straightforward and intuitive to facilitate user interaction. The problem at this time was compounded by the fact that computing power and graphics possibilities were extremely limited by comparison with the current situation, and despite the fact that the basic engineering science and mathematics have not changed, attitudes to issues such as comfort have developed in terms of a drive for greater occupant control and intervention.

In addition, the developers and users of these models traditionally approach the problem from completely different standpoints – the users from a design-orientated perspective and the developers from a scientific standpoint focused on technical rigour. The situation is further complicated by the different terminology of the scientific, engineering and design professions. This resulted in an impasse, which restricted routine tool use by anyone other than specialists and researchers/ tool developers, in that, the data input process was neither user-friendly nor familiar to design practitioners. The tools also required detailed, precise input information from users regardless of the design stage or application domain.

In the early 1990s in Europe and internationally, prompted by the rapid and enthusiastic response within the architectural and environmental engineering professions to the emergence of CAD tools, a number of research projects began to explore the possibility of developing 'intelligent' interfaces that would simplify and support users who were at that time hampered by the limitations of existing interfaces. Secondly, despite the limitations of computing capabilities at that time, research was also underway into the possibilities for tool interoperability through the creation of an integrated product model (IPM) that would facilitate dialogue between design tools and the various design disciplines. The aim was to simplify interactions between users and input requirements with a view to developing tools that were more user-friendly than in the past, and which were also linked to centralised data models that could support tool interoperability.

5.2.1 An intelligent front end

In the late 1980s, a number of research projects Europe and Worldwide, explored the development of bespoke interfaces, databases and 'rule bases', in order to simplify and manage data input, thus protecting the user from the vagaries of the various applications employed throughout the design process. These projects included AEDOT (US) (Brambley, 1988), and LEARNSIM (Jankovic, 1991) but the key projects relating to the European professions were the IFe (Integrated Front-end for Building Simulation (Clarke and MacRandal 1989), and COMBINE (Computer Models for the Building Industry in Europe) (Augenbroe 1991, Clarke *et al* 1995).

Using an Intelligent Front End (IFE), it was envisaged that energy simulation models would be more flexible, allowing the use of simplified tools to test early stage design hypotheses but also enabling more detailed analysis without repeating data input at later stages as the design evolved, with a view to moving one step closer to the development of a fully integrated approach to computer-aided building design. The ultimate objective was to produce a system that was familiar to practitioners in terms of input requirements and which at the same time, provided support at all stages of the design process, in other words, an intelligent front end (IFE) to interface between the user and a detailed building energy simulation application. Ideally it was envisaged that an IFE would replace the expert support provided in the past by a human interface through mechanisms such as EDAS and SESG, with a machine environment which would fulfil the same function, assisting the user through the problem definition phase, anticipating/ pre-empting appraisal questions, invoking integrated analyses and assisting users to turn output results into design decisions, at all stages in the design process.

To achieve this requires that the IFE appears user-friendly and, in order to address all stages of the process, it must be suitable for use at all stages.

However, despite some success it is apparent that accomplishing an IFE for routine use in practice is easier said than done, and in attempting to be all things to all people, such an interface carries with it a number of risks:

- the risk that the power and flexibility of models will be adversely affected by limiting the number of choices and interactions that users can make;

- the risk that users will be misled by the apparent ‘simplicity’ or user friendliness of the interface, and may as a result underestimate the potential significant impact of the decisions made regarding to data inputs; and
- an associated obscured mismatch between user knowledge and tool power.

The support mechanisms in place at the present time have been shown to facilitate the management of these risks, but were these mechanisms to disappear, the elimination of such risks would ultimately require truly intelligent systems, with interfaces that can manage users questions and expectations.

5.2.2 Centralised data storage and exchange

The potential for development of an Intelligent, Integrated Building Design System (IIBDS) was further explored within the European COMBINE (Computer Models for the Building Industry in Europe) Project (Augenbroe 1995, Clarke, *et al* 1995).

The COMBINE project maintained that there were two main issues to be resolved in order that design tools can be used in cooperative mode, and that these required mutual communication with one another. Firstly, the need to put in place a single, consistent model of a building and its systems from which disparate design tools can obtain their inputs and return their output, and secondly, the requirement to manage the transactions between users and design tools.

The project objective was thus to facilitate ongoing analysis using different tools as designs evolved and as analysis requirements increased in complexity. Key elements of the project were: the development of the central data storage bank or Integrated Data Model (IDM), in order to allow a project to grow over time and yet to allow data to be stored and extracted as required into whatever modelling tool was being applied at that stage in the design process; and to allow users to be protected from the vagaries of the poorly developed data input systems/ interfaces of the time by providing them with the facility of a computational support environment in the form of an intelligent, integrated building design system. The IIBDS at that time incorporated the facility to coordinate designer-to-designer, designer-to-application and application-to-application transactions, enabled through a set of rules set up within the system (Hand 1999, Augenbroe 1992, 1994).

5.2.3 Knowledge based systems

Knowledge based systems either 'contain' or (ideally), 'learn' how to guide a user, directing the line of enquiry by building upon past responses. In theory, this allows "*What do you suggest?*" and "*Why do you ask?*" type responses. But despite vast improvements in computing power, even the most recent advances in Intelligent Knowledge Based System (IKBS) and Human-Computer Interface (HCI) techniques offer only limited scope for this from a user perspective. In order to reach their potential, such techniques require a significant level of knowledge in relation to building description, but in the face of real world uncertainty and realistic performance assessment methodologies, this information is not generally available at the point when it can be of greatest influence on the design. Nevertheless, such systems can already (at the time of writing), be expert enough to assist users to devise an appropriate performance assessment methodology and to coordinate model operation against this.

5.2.4 Summary of lessons learned

While computing systems in the 1990s were (in theory) able to allow researchers to develop both programs that could allow them to undertake various aspects of energy simulation, the existing interfaces were primitive by comparison with what was required to deliver an IFE. In addition, while various aspects of a design could be modelled independently, the fact remained that there was no consensus on programming language at this time which made it difficult to transfer data between programs, and thus considerable effort was required if the tools in question were to 'speak' to one another – notwithstanding the fact that the creation of integrated, multi-faceted tools would have an impact on speed and ease of use. The situation was compounded by the fact that the simulation profession was a long way from agreeing on what were the best programming languages and approaches to use as new ideas were emerging all the time.

In addition, while computer graphic capabilities were advancing apace this apparent power belied the fact that (for a time at least) graphic capabilities 'ate up' computer memory and this power was accessible only in the world of workstations rather than PCs, which were just beginning to emerge as everyday tools. It was thus *possible* to access reasonably good graphics or to access powerful computational capabilities, but the reality was that the integrated IFE and the centralised data model were theoretically possible but were just out of reach for most researchers, let alone designers.

In summary, the difficulties with delivering user-friendly tools at this time were a combination of a lack of access to the necessary computing power, the cumbersome nature of the existing programs and the fact that such a system would have required a quality of graphics not readily available on desktop computers at that time and certainly not at affordable prices – thus the need for expensive workstations. The scale of the COMBINE project was to an extent hampered by the limitations of the computing systems of that time, but it did open up a whole avenue for research by growing an interest in the professions of what might be possible, and while the components never quite worked fully together, it was demonstrated that in the future they would have access to powerful tools with user-friendly interfaces. At the same time, it also raised questions as to the accompanying risks of delivering this much desired 'solution' to the professions, without an associated understanding of the power of the tools or the complexity of the thermodynamic interchanges from which they were protected by interfaces.

In the last 15 years, what was perhaps a pipedream has become a reality in some senses. There are many designers and researchers who believe that the development of better CAD interchange mechanisms to support geometry input and more user-friendly interfaces have to an extent solved the professions' problems in relation to simulation use in design practice, and who also perceive that those problems that remain will be dealt with by similar mechanisms in the fullness of time (Morbitzer 2003, Hobbs *et al* 2003). Indeed, many of the problems relating to software and hardware incompatibilities, inadequate power and graphics and accessibility to high power processors have been resolved, and many simulation applications and calculation tools either use or are compatible with the much improved CAD tools now available for geometry input. There is also a reduced likelihood of programming language issues, in part because it is easier for different programs to communicate with one another through a medium such as a CAD model, and, in part because the languages in use have to a degree been standardised. Further, there is a greater consensus on approach to model development linked to the availability of CAD interfaces that can be more readily linked to geometry input file requirements and object oriented CAD files to which surface and material properties can be added. While all of this goes some way to alleviating the impact of tool accessibility, it does not address the fact that many of those using simulation tools do not fully understand the thermodynamics of buildings.

Since the COMBINE/ IFE research of the 1990s and the drive to develop mechanisms that would deliver user friendly tools to the professions, in some respects the world has moved on. There now exist many, including the author, who on the basis of researching and effecting the delivery of simulation into the hands of the professions, would now argue that as tools become more user-friendly, it is vital the potential users of these tools understand the potential risks of ‘mis-use’. If a tool appears ‘simple’ then an uneducated user could quite reasonably assume that it is not only easy to use, but also straightforward, and thus the user may not apply sufficient rigour in selecting input data. It may be argued that if the interface is easy to use, then it is easy to revise the model data, and to re-run the simulation. However, in practice the response to a quick answer is often to either accept the output, file the ‘answer’ and walk away, or to set it aside with the intention of returning – but not doing so. In addition, if the tool is simple to use, it is less likely that the same degree of rigour will be applied to quality assurance, simulation procedures and methodology for approaching the process as would be applied in the case of a complex data input process, on the grounds the user will remember what he or she did, which six months later, is most unlikely.

This is not to suggest that there is no need to develop better interfaces. However it is interesting to note that one of the respondents to the monitoring survey carried out as part of the second phase of the research in 2008, reported after the interviews that he and his staff saw greater value in mastering a complex but fully flexible tool, rather than being tied into a commercial package, which lacked transparency despite apparent ease of use (Shearer 2008[2]). Similarly in association with recent training courses to which the author contributed, it was observed that despite intensive training in the use of the simplified tool, rdSAP (BRE 2009) for Energy Performance Certification under the

[2] Shearer T, 2008, personal communication November 2008.

requirements of the EPBD, evidence from the trial training example showed that it was still possible to fail the course (Tuohy 2009[3]).

Based on this and other similar evidence and experience over the last 20 years of experience gained through this research, it is conjectured that the successful delivery of simulation to the professions is predicated upon the continuation of an approach based on better support mechanisms for use in practice, as advocated by phases 1 and 2 of the research, plus: continuing improvements in interfaces; improved in-house quality assurance procedures; including data storage; archival and retrieval systems; and mechanisms to assist designers with the interpretation of simulation results and how best to use these to inform design decision making.

5.3 Ongoing issues

Even the most advanced and fully integrated simulation applications do not fully support users in either the management of input and output data or by providing feedback at all stages during model development and throughout the design process. In terms of advanced support, such as bringing to the attention of users issues relating to illogical or inaccurate data; and procedures to facilitate management, storage, archival and retrieval systems to allow projects to be revisited by *any* user, all users, expert and novice alike require:

– *Integrated quality assurance systems* – to support the development of transparent management systems and documentation procedures in simulation. This has been

[3] Touhy P, 2009, Personal communication February 2009.

discussed at length in Chapter 4 and will continue to play a pivotal role in guaranteeing the future of simulation modelling in industry;

- *Performance assessment methods* - the further development of transparent documentation procedures in simulation to guarantee the future of simulation modelling in industry, including: initial planning and ongoing supervision mechanisms to help ensure successful control of the overall simulation strategy and the establishment of effective and efficient simulation management, archival and retrieval systems;
- *Integrated performance views* – the further development of IPVs towards the notion of the *Integrated Intelligent and Interactive performance views* reported in the work of Prazeres (2006) to support emerging Intelligent Knowledge Based System (IKBS) and Human-Computer Interface (HCI) techniques by providing multi dimensional interactive mechanisms to compare results from integrated simulations;
- continued development of data interchange facilities and improvement of interfaces to better support users;
- adequate support and training to make best use of all of the above.

In order to:

- inform professionals new to simulation of the required information to initiate a model;
- ensure that other members of the design team (and the ultimate users of the built environment) can view input data and results at all times, and can query them as appropriate;

- provide a mechanism to facilitate cross-checking of data as it is input to the application in use, serving as a tool to ensure that simulation models are consistent, and accurate;
- create models that are flexible and remain useful throughout the design process; and ultimately
- develop better building benchmarks.

Were all of the above to be achieved, would this alleviate the existing barriers to tool use in practice? Probably not, as buildings and their systems are much more complex than even many experienced designers perceive. However, achieving all of the above would address many of the time related barriers, allowing designers to get up to speed quickly and if systems were rigorously applied, to re-visit archived work with relative ease.

The supported computational approach as advocated within the research addresses the integration of the computational skills required to quantify building environmental performance. However, it does not address the fact that the number of sustainable buildings being delivered is still relatively low, despite design briefs that call for sustainability. Research shows that in practice, perhaps due to lack of control or poor communication, there persists a tendency not to see things through (Scottish Government 2004). The reasons for this are manifold and range from: lack of understanding of what sustainability means; to over simplification of the issues; mis-information regarding sustainability and a failure to ensure that the sustainable design intent is carried through and revisited at each stage of the process.

5.4 Influencing factors

Many of those commissioning and designing ‘green’ buildings think of sustainability as an add-on, such as the addition of anything from insulation to heat pumps, wind-turbine or photovoltaics, to a traditional design. Rather, sustainable development is about the creation of better places where people feel confident and have aspiration – places where people will want to live now and in future, even if their circumstances change – learning communities. Low ecological footprint is undoubtedly an important feature of these communities, but if not balanced by these other factors, green buildings alone do not create sustainable communities. To achieve an excellent outcome requires a process that incorporates client participation and consultation from the outset and throughout delivery, including post occupancy. A true consultation process develops ownership and positive attitudes in users and stakeholders. And through appropriate consultation, issues associated with sustainability - from energy in use, through healthy materials and interaction with the external environment and biodiversity to longevity for the building - will automatically be considered. Conversely, a lack of strategic process in consultation undermines our belief in the validity of the experience of users (Cunningham 2005). Sustainable development is thus a process that requires constant vigilance and re-evaluation at every stage in order to avoid ‘dropping the ball’. It involves users, designers, new and old technologies and many other socio- economic- drivers that are not (yet) within the domain of simulation.

“Bad design is expensive - it is not like bad television, you cannot switch it off. It continues to infect our lives”, (Macdonald 2005). A good architect can design a good building, but ‘good’ is like ’nice’, lacking in inspiration. The combination of a good

design team and contractor, with access to the right tools and design support with an informed client can result in an excellent outcome. Sustainability should be inherent in design excellence.

5.4.1 Sustainability in Architecture

Sustainability in Architecture (Sust. 2005) is a Scottish Government funded project, devised to be consistent with its approach to sustainable development as outlined in the 'Meeting the Needs' document (Scottish Government 2002) and Our Common Future (Scottish Government 2005). Sust. promotes a sustainable approach to design in the built environment and to assist all those designing and commissioning buildings in delivery of buildings that meet the expectations of all involved.

The Sust. initiative aims to enable its clients (developers, community groups and designers) to take a more integrated and holistic approach to the design and management of the built environment with a view to promoting a fundamental shift in thinking about sustainable design. Projects put in place include: tools, techniques and guidance to assist all building stakeholders to make the necessary changes to their approaches and work practices - in effect to mainstream sustainable development. Now, Sust. is informing the direction of the research in order to maximise the potential combined impact at the implementation stage of a project and to improve opportunities for working more closely with the architectural profession, providing them with greater access to early stage design tools, in order to improve their understanding of sustainable design issues.

It is envisaged that through such collaboration, it will be possible to build a greater appreciation of the opportunities that simulation can offer, while making designers aware of the risks associated with such powerful technologies.

Support for all of this is available through such guides as CIBSE Technical Memorandum - *TM33: Tests for Software Verification and Accreditation* (CIBSE 2006), which describes a series of standard tests for commercial software calculation tools. The aim is to verify that such tools produce results consistent with good practice and are consistent with the methods in the CIBSE Guides.

The main focus is on thermal performance of buildings. The tests were developed with the intention of finding a balance between comprehensiveness and ease of application. The main reason for the tests is to build confidence in tool users, rather than providing a comprehensive validation of a program.

The next goal is to continue to facilitate delivery of more sustainable buildings by improving understanding of what this means in a language appropriate to different audiences. The aim is to engender a need for performance quantification in practices without the capabilities to adopt the tools in-house, and for the outputs of simulation to be translated into a form that is both appealing and useful to building users and the wider community.

Sustainable development is not just about the environment, materials or energy, or about costs and jobs or creating places that people will love – it's about balancing all of these things so that when we create these spaces people will love them and cherish them and they will last – and we won't have to waste energy in taking them apart and putting them in landfill sites and starting again in 20 years. As for the future, it is incumbent on us to take responsibility for our actions at all levels.

5.4.2 Software research and development needs

Spin-offs in terms of future research need include but are not restricted to:

- Ongoing updates to, and tighter regulation from Europe through the implementation of the next phase of the European Energy Performance of Buildings Directive and associated national legislation.
- The associated drive for low carbon technologies ranging from conventional devices such as heat recovery schemes through novel systems such as combined heat and power and air/ ground source heat pumps.
- Demand reduction in its various forms from increased equipment efficiency to demand side management using remote switching technologies.
- The ability to inform citizen health and wellbeing issues with the focus on tools for the study of environmental emissions, air quality, human comfort and building evacuation, for example.

5.5 Conclusions

Over the past 20 years simulation tools and skills have moved from the academic domain into specialists practices and are now in use by general consulting engineers.

The two phases of research reported here progressively tackled many of the perceived barriers to the uptake of simulation. In addition, these initiatives have demonstrated in practice, that simulation-based design can undoubtedly yield results, *quicker, cheaper* *and better* than conventional methods, but not without considerable fortitude from the businesses involved. This has resulted in enhanced design quality, and (more importantly) increased business for participating companies. This success is in part due to the partnering and mentoring scheme offered through the projects and in part to the 'buy-in' of company directors, and design staff, to the need for the development and rigorous application of a procedure for use of simulation in practice, backed up by checks and balances in the form of quality assurance and benchmarking.

If the deployment of energy and environmental simulation is to increase within industry, it will lean heavily on the effectiveness of establishing efficient simulation management systems. Initial planning and ongoing supervision will help ensure that companies can successfully control the overall simulation strategy.

Despite a number of previous initiatives that have explored the possibilities, current system configuration does not yet facilitate checking of input and output data within a simulation model with regard to illogical or inaccurate data. This makes it difficult to 'get up to speed' with simulation projects initiated by someone else, resulting in a reluctance to get involved in someone else's project. Therefore, the development of transparent documentation procedures in simulation will play a pivotal role in guaranteeing the future of simulation modelling in industry. Performance assessment methods and QA procedures are seen as a positive step to removing some of the 'mystery' associated with simulation data input and in addition, as a suitable management system to compliment the ever-improving documentation, archiving and retrieval procedures of current simulation tools. It is not envisaged that this will replace the need for an expert to oversee the overall simulation strategy, but it should enable users to step in and out of any simulation with far greater ease than is currently the case. One concern that both academic and industrial users alike are keen to avoid is the duplication of data input as this is detrimental to the overall efficiency of the process. If professionals do not understand the simulation process they cannot easily use simulation results to inform their design (Donn 1999). With this in mind the anticipated benefit of Performance Assessment Methods (PAMs) is threefold in that they:

- will inform professionals new to simulation of the required information to initiate a simulation model;
- will ensure that other members of the design team can view input data and results at all times, and can query them as appropriate; and
- can be used as a reference to cross-check data input into a simulation model serving as a tool to ensure that simulation models are consistent and accurate.

This thesis has reported observational research into the use of simulation in design practice over a period of almost 20 years. The research has supported the embedding of simulation in design practice by transforming simulation support from a specialist activity to a routine part of the design process. Further, the research has contributed to the development of quality assurance methods for tool use in practice over this period. Finally, the research has also facilitated the development of performance assessment procedures in support of this work. The key outcomes are contributions in the following areas:

2. Understanding the barriers to tool use in practice and helping the professions to overcome these. This work was undertaken through observational research into the use of simulation in practice over 20 years.

3. Contributions to development of quality assurance procedures for use in practice. Quality assurance was the single biggest issue outside of the technical competencies of models at the start of the research. The industry would not adopt a simulation approach to design if it could not assure the quality of the advice given on the basis of the results. Quality assurance procedures were developed to observe, document and improve the process. The research makes two contributions in this regard:
    c. The development of quality assurance procedures for selecting consultants and for managing the process of the consultant/ customer relationship – BS 5750/ ISO 9001 – was the industry standard. Initially wanted to get straight in to the heart of assuring the quality of work done on behalf of design teams, but very quickly it emerged that this was impossible without a procedure for selecting specialists in the first instance.
    d. Assistance with the development of appropriate quality assurance procedures for the application of simulation methodologies and procedures in practice. These procedures make sure that the simulation methodologies and procedures are applied in accordance with an agreed system. Simulation methodologies and procedures can exist without QA, but QA helps to identify and trap errors in the system, and if correctly applied, can include decision support.
4. In support of QA a Performance Assessment Method or PAM can further support use in design practice by directing the user's line of inquiry. The research contributes to

the development of simulation performance assessment methods and procedures by identifying industry needs and issues associated with use by practitioners and feeding this back to researchers in the field to better inform new application methods in terms of who does what, why, when and where - working as conduit between industry and companies – which allowed information flow in two directions.

5. The fourth contribution is to the ongoing development of integrated performance views (IPVs) for practitioner and client use. Prior to the advent of integrated tools practitioners were already recognising the need to compare and contrast results from different modelling assessment programs – e.g. lighting and thermal, impact on energy consumption of renewable integration and risk of glare associated with daylight use, for example.

   Early observations of use in practice supported the academic perception of a need for mechanisms to bring together results in one place in the absence of integrated tools at the time through IPVs. Most importantly, industry dialogue and focus group observations gave rise to the need to display information in a meaningful way, and to inform what information was important to practitioners at large depending on the audience. For example, while architects might want to see images and engineers numbers and graphs, a client may relate better to something that he or she reflects their building in appearance before trusting any figures. What will be right for one customer will not suit another.

From the mechanisms outlined in this thesis, the following conclusions are drawn:

- contemporary simulation systems can be cost-effectively deployed where appropriate support is available;
- the largest portion of the cost relates to staff training, not to the acquisition of hardware and software;
- a change in work practices is needed if the profession is to move to a new best practice based on a computational model of design;
- barriers and bottlenecks can be minimized through training support and by setting achievable goals;
- finally, the use of a forum that provides tool designers with access to a mixed audience of practitioners through which evolving design tools can be evaluated has proved highly beneficial and is likely to be even more relevant in future as impending legislation imposes tighter emissions controls and as integrated performance assessment becomes enshrined in practice.

The purpose was not to explore what we do, but to change the way we do it.

"What is the point of developing powerful tools without putting in place the means to train and support users? What is the point of deploying advanced IT methods within an outdated approach to work-flow management? There is no point." (Clarke 2001).

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APPENDICES