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Energy Simulation in Building Design

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Abstract

Design decision support related to building energy consumption and / or indoor climate, should be based on an integral approach of environment, building, heating, ventilating and air-conditioning (HVAC) system and occupants.
The tools to achieve this are now available in the form of computer simulation systems which treat the building and plant as an integrated, dynamic system. Although its potentials reach beyond the area of Computer Aided Building Design, the paper describes building and plant energy simulation simulation within the context of CABD, design decision support and design evaluation.
Currently, computer simulation is only used indirectly as a design decision support mechanism; ie its power is not delivered very efficiently to the design profession.
Future research directions are indicated, aimed at providing a mechanism to overcome this problem by developing an "intelligent front end" which bridges the gap between sophisticated computer simulation tools and the design profession.

INTRODUCTION

The dynamic thermal interaction, under the influence of occupant behaviour and outdoor climate, between the building and its heating, ventilating and air conditioning (HVAC) system is still difficult to predict. In practice, this often results in non-optimal, malfunctioning, or even "wrong" building / system combinations. Other topics belonging to the same problem domain are (in no particular order): Sick Building Syndrome, Building Energy Management Systems, application of passive solar energy, HVAC system and control development and testing, integrated systems (eg floor heating, ice rinks, swimming pools), and unusual building / system combinations which may occur for instance when a historical building finds a new use (eg a church being converted into a multi-purpose centre) or in case of relatively new developments like atria.
The above mentioned problems and the need for an integral design approach of building, HVAC system and occupants, are becoming more and more important. Therefor a research project was initiated on development / enhancement of building performance evaluation tools which treat the building and plant as an integrated, dynamic system (Hensen 1991).

One of the techniques available, is modelling and simulation.† Currently the most powerful tool available

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† Modelling is the art of developing a model which faithfully represents a complex system. Simulation is the process of using the model to analyze and predict the behaviour of the real system.

for the analysis and design of complex systems, is computer simulation.

Modelling and simulation have become indispensable engineering techniques in the fields of design (eg of buildings, plant configurations, and on the component level) and operation (system control, understanding, and interaction). The main reasons for this are that these techniques offer vast advantages - over for example experimentation - with respect to:

- economy; in an increasing number of cases, simulation is faster, better and cheaper than experimentation,
- prediction; allows analysis of a (model of a) system which does not yet exist, and
- education; models are easily adapted, inexpensive to operate, able to simulate adverse conditions and may also serve as an aid in communication.

Of course simulation and experimentation are effectively complementary: experimentation to discover new unknown phenomena or for validation purposes, and simulation to understand interactions of the known components of a system.

In the current context, modelling and simulation is thus used for predictions in order to support design decisions on real world problems regarding buildings and the HVAC systems which service them. The building in question may be an existing structure, a proposed modification of an existing structure, or a new design.

Although the potentials of building and plant energy simulation reach beyond the area of Computer Aided Building Design, here we will describe simulation within the context of CABD, decision support and design evaluation.

THE CABD CONTEXT

Since the early 1960's, the use of computers in the field of building design - ie CAD (Computer Aided Design) which was only later specified to CABD (Computer Aided Building Design) - has been increasing steadily (Rooney and Steadman 1987). Although, according to Gero (1983), its potential has and is taking longer to realise than was first thought. This statement is still true, judging from comparison of Gero's predictions for the then immediate future of 1983 with the actual situation at present (see eg Ratford 1991).

Having mentioned this, CAD in the field of building design has received more and more attention, both from research and commercial communities. Due to economic factors, the draughting function has received the most - commercial - attention and is now becoming well established in building design practices.

The design process itself is very complicated, as may be concluded from the vast amount of work aimed at establishing models of the process of design. As Butera (1990) points out, the architectural design process may even be approached using principles from the so-called "deterministic chaos" theory. The complexity and the diversity of parameters to be taken into account leave large opportunities to chance in identifying the design optimum. The optimum may be regarded as a "strange attractor" in this context.

Due to its complexity, general software to aid in the design process, is much less developed and received much less attention than draughting and design process management tools. In recent years promising research activities have been - or are about to be - initiated aimed at relieving this deficiency. These studies often involve pluri-disciplinary research teams and employ very sophisticated research techniques (eg Dubois 1990, and Clarke and Duffy et al. 1991).

There is however one activity throughout the design process which has received much attention: building performance appraisal. Powerful, computer-based models were created to assess cost, performance and visual impact issues in design: from life-cycle cost estimates at the design proposal stage, through realistic visualisations of the design, to comprehensive evaluations of building energy and environmental performance. A demand for systems which possess both draughting and appraisal functions is however steadily growing. In response, appraisal programs were appended to draughting packages, thus creating what we may call early CABD systems.

As elaborated by Clarke (1989), CABD, and the sub-systems which it comprises, are affected by continuous changes in: power and cost of hardware, quality of software, elegance and effectiveness of human-computer interfaces (HCI), and user interface management systems (UIMS), and in (computer aided) software engineering (CASE) methods with which a greater degree of sub-system integration is possible. Table 1 (Clarke 1989), which is self-explanatory, summarizes several of the important issues in this respect.

Table 1 Issues underlying CABD evolution (Clarke 1989)

Issue	Time Scale			
	Immediate (now)	Short-term (now-5 years)	Mid-term (5-10 years)	Long-term (10^+ years)
Technology	• Micros • Drafting • Early performance prediction	• Supermicros • Partial CAD integration • Early expert systems	• Networking (worldwide) • Expert systems • Full CAD integration	• Computer ubiquity • Artificial Intelligence • Natural language • Full IKBS
Applications	• Drafting • Information technology • Performance prediction	• 'Accredited' performance prediction • 3-D Visualisation • Regulations	• Performance specification • Solids modelling • Integrated functions	• Participation • Client-orientated CABD • Post occupancy applications
Education and training	• Applications exploration • Hardware familiarisation	• In-depth postgraduate training	• Advanced undergraduate & mid-career training	• Full computer assisted design systems
Research	• Application knowledge • Validation • System evaluation	• Human-orientated CAD • UIMS, Shells Environments &	• Systems for computer-naive designers • Implementation environments	• Non-traditional communication • Design optimisation
Impact	• Expensive & time consuming • Job shifts	• Skills shortage	• De-skilling • Breakdown of professional boundaries	• De-professionalisation
Net result				• Improved product performance

When this table is projected on the actual situation at present, it seems that we are already in the short-term or perhaps even mid-term columns as far as the technology is concerned. This is due to recent technological and economical developments: ie relatively inexpensive, high performance, graphics workstations, strong reduction of data storage costs, and emergence of early expert systems (see eg Mac Randal 1988). To further illustrate this: at the start of the present work (late 1986) a high-resolution, bit-mapped, graphics workstation, offering a performance of 1.5 Mips (million instructions per second) and 70 Mbyte data storage, was purchased for approximately 20 kECU (≈ fl 50000). Now, 5 years later, two new workstations have been ordered one of which is only half the price and offers a 15 Mips performance, and another which still costs 20 kECU but offers 28 Mips performance and 1 Gbyte of disk storage capacity, instead.

As another exemplification of fast developing technology consider the following quote from Hartman (1988), which in addition illustrates usage of worldwide networking as may be deducted from the reference:

> *Technology which seems unearthly and ethereal today will be reality and commonplace tomorrow. Fiberoptics and electronic imaging will allow us instant access to networks and information systems throughout the world. CD-ROM, WORM, and huge optical disks will provide mass storage capabilities with speedy searching and retrieval. Animation, simulation, video and voice input and output, and supercomputer power will be focused on the desktop. And while computer processing will become decentralized as workstations continue to proliferate, networks and shared systems will weave strength into our interdependence. Not technology for technology's sake, but more people performing more computing and incorporating computers in new and innovative ways in the pursuit of excellence in teaching and research.*

With respect to applications ,in 1992, we still seem to be in the "immediate" column, except perhaps for 3-D visualisation which appears to be the next commercial goal (ie following draughting). The same is true for education and training, where as yet, only few educational institutions offer in-depth postgraduate training.

Regardless of technological developments, CABD will not become commonplace unless there is a high standard of user training. Although, as pointed out by Clarke (1989), it could be that ultimately user training becomes less important due to high level assistance by the computer. This does not imply however, that setting-up of education and training schemes is not of the utmost importance now.

With respect to research, up to now the majority of activity is directed towards proving the system and towards the acquisition of application knowledge. In the field of building energy simulation for example, a number of projects concerned with model validation have been or are being carried out.

Currently there are indications that the building energy simulation research activity is broadening in its scope (see eg Augenbroe and Laret 1989, and Clarke and Maver 1991). More effort is being expended on human-orientated CABD, through expert systems, HCI research and the like (eg Clarke and Rutherford et al. 1989). There is also a greater tendency to approach the problems underlying CABD in a multi-disciplinary, inter-institutional manner (e.g. Clarke and Hirsch et al. 1986, Clarke and Irving et al. 1988, and Augenbroe and Winkelmann 1990). This is also reflected in the recent formation of building analysis clubs: International Building Performance Simulation Association (IBPSA) based in the United States, Building Environmental Performance Analysis Club (BEPAC) in the United Kingdom and Building Analysis Groups (BAG) in the Benelux.

CABD is not a remedy for all difficulties. At worst it is an automation of much of the mechanics of design. At best it allows an evaluation of the relationships inherent in a given design hypothesis. At present, the application of CABD is expensive, in terms of required human resource, and time consuming. In the near future the profession will probably experience a skills shortage. In the longer term however, with further advances in technology, application knowledge and education and training, CABD might bring important changes in the design process, involving de-skilling and the breakdown of professional boundaries. CABD could well become the common denominator of all parties involved in the design process, through some future IIBDS (Integrated Intelligent Building Design System). This will lower or even remove inter-professional barriers and improve the quality of the end product, the building.

As indicated, CABD is an evolutionary process which is characterised by several strong interrelations between quite different issues. For example, the level of application of energy simulation is as much a function of education and training as it is of hardware and HCI. Of course, CABD must also be regarded in the light of other technological and other developments which are taking place around us. That is, CABD will certainly become integrated in the "office of the future" which might offer multi-media personal work environments, incorporating integrated CAD/CAE (Computer Aided Engineering) features.

One important issue not yet mentioned yet is that of politics. There are trends towards requiring that specified conditions must be achieved during the operation of buildings as well as in the design of buildings (as in ASHRAE's 1989 standard on ventilation and air quality, and towards setting up "responsibility chains", ultimately making a design team liable for the performance of the end product (as implied in for instance ASHRAE's (1989) guideline for commissioning of HVAC systems). It could well be that if these

trends are followed and accepted by the building industry, such issues will become major catalysts in the evolution of CABD.
Building energy simulation must be placed within this evolutionary context. Contemporary energy models are an important improvement compared with the traditional methods they replace. However, there are still several important developments which must be undertaken before valid, easy to use models can be delivered to the design profession.

BUILDING ENERGY SIMULATION

As indicated in the introduction, modelling and simulation have become popular engineering tools since they permit us to predict the behaviour of a system before the conditions we are interested in occur, and indeed even without the system actually existing. In fact, modelling and simulation are the only techniques available that allow us to analyze arbitrarily non-linear systems accurately and under varying experimental conditions.

Simulation is used in many areas of science and engineering. It is used in different senses to study a variety of systems which may be classified as: continuous vs discrete, deterministic vs stochastic, or dynamic vs steady-state. It may be clear that building energy simulation addresses very complicated, highly interacting, continuous, deterministic, dynamic systems.

Table 2 The evolution of building energy models (Clarke 1988)

1st generation	Handbook orientated		Indicative
	Analytical in formulation	<----	Application limited
	As simplified as possible	|	Difficult to use
	Piecemeal in approach	|	|
2nd generation	Dynamics important	Feedback loop	|
	Still analytical	|	|
	Still piecemeal	>----	Increasing integrity
	Suitable for low-order problems	|	vis-à-vis the real
	with time invariance	|	world
3rd generation	Field problem approach	|	|
(current generation)	requiring numerical methods	|	|
	Integrated view of energy	|	|
	sub-system	|	|
	Suitable for high-order problems	>----	Leading to
	with time variation	|	|
	Heat and mass transfer considered	|	|
	Better user interface and partial CABD	|	|
	integration	|	V
Next generation	Full CABD integration	|	Predictive
	More advanced numerical methods	Feedback loop	Generalized
	Intelligent knowledge-based	>-----	Easy to use
	Object-orientated software		
	architecture		

Building energy modelling and simulation is part of an evolutionary process in the field of building design tools. Table 2 (from Clarke 1988) summarizes one view of the evolution of these design tools, from the traditional via the present day simulation approach to the 4th generation tools by the late 90s.
More information on the state of the art in building energy simulation can be found in reviews by Winkelmann (1988), and Wiltshire and Wright (1988).

Early work in current generation approaches, focussed on the relation between building design and energy consumption (eg Clarke 1977, Bruggen 1978), or between building design and thermal comfort (eg Lammers 1978). In this and in later work (eg Hoen 1987), the auxiliary system was still more or less regarded as a given boundary condition instead of as a variable. These workers emphasized the building side of the overall problem domain, while others (eg McLean 1982, Murray 1984, Tang 1985, Lebrun 1988) focussed more on the plant side.

In the former approach the influence of the plant system is more or less neglected by over-simplification; estimation of energy consumption is based on some presumed, imposed indoor air temperature profile. In the latter approach the complex building energy flow paths are usually grossly simplified, and the building (or each building zone) is commonly regarded as just another plant component which in this case imposes a thermal load on the system.

Although justifiable at that time, it is now felt that neither approach is preferable for the majority of problems which are affected by the thermal interaction of building structure and auxiliary system. We started from the principle that both building and plant have to be approached on equal levels of complexity and detail while taking into account all major fluid flow and heat transfer couplings.

For the present work, we started from an established building energy simulation environment and enhanced this on the plant simulation side of the overall problem domain: the ESP^R (Environmental Systems Performance, Research version) energy simulation environment (Clarke et al. 1991), a system which is currently under development at various research centres throughout Europe among which the Universities of Strathclyde and Eindhoven.

Reporting this work, Hensen (1991) describes a "modular-simultaneous" technique for the simulation of combined heat and fluid flow in a building / plant context. The present performance of the system indicates that it is practical to solve the building / plant heat and mass flow network in detail. Moreover, the solution of complex building / plant / fluid flow networks in the transient state is now feasible on inexpensive computers. This enables an integral approach of the thermal interaction of building structure and heating and ventilating systems, and also provides the basis / power for design decision support in this area.

DESIGN SUPPORT VIA SIMULATION

In the field of building energy related issues, there is a certain tradition of using computer simulation for design support, involving the generation of knowledge which is subsequently transferred to the design profession. This kind of design support is thus based on knowledge transfer from "specialists" in a certain part of the overall problem domain, towards the design profession. With respect to the transfer process itself, there are may different approaches. At one end of the spectrum of possibilities one finds the so-called design-aids, while consultancy work for a specific design could be located at the other end of the spectrum. To demonstrate both these approaches by an example:

Design-Aids

This is a form of knowledge transfer in which the "specialists" try to generate generic knowledge which is supposed to be suitable for a range of buildings and which is usually aimed at being used by the designers. This kind of knowledge is commonly based on regression techniques applied to the results of multiple parametric runs of more powerful modelling systems. The results to emerge can often be reduced to simple relationships or presented in tabular or graphical form. Figure 1 is a typical example (from CEC 1986) showing summer overheating assessment graphs for medium-weight houses.

It is obvious however, that there are a number of drawbacks from such an approach, the most important ones being: (1) a particular aspect is regarded in an isolated manner, (2) this approach is only possible for a limited number of variables, and (3) the results are only valid for a certain combination of environment, building, installation, and occupancy pattern which is quite similar to the one used to generate the results.

Consultancy Work

In the current context this involves the generation of specific knowledge for a particular design by a specialist. Work we did on predicting air flow through proposed shopping arcades; ie the

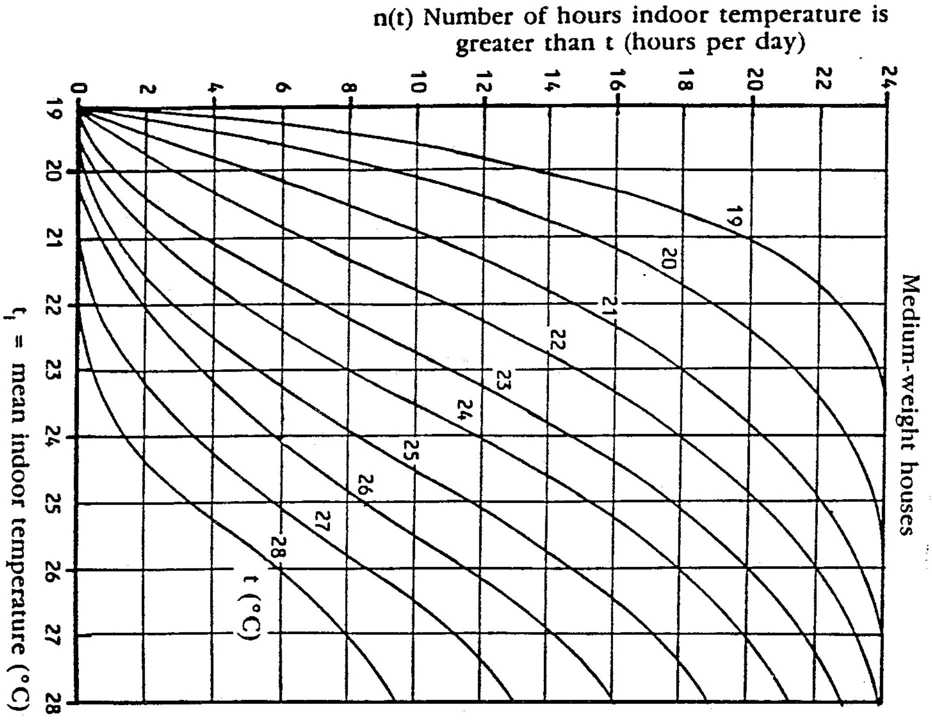

Figure 1 Summer overheating assessment graphs for medium-weight houses (from CEC 1986)

Heuvelgalerie in Eindhoven (Figure 2), is a typical example of such approach.

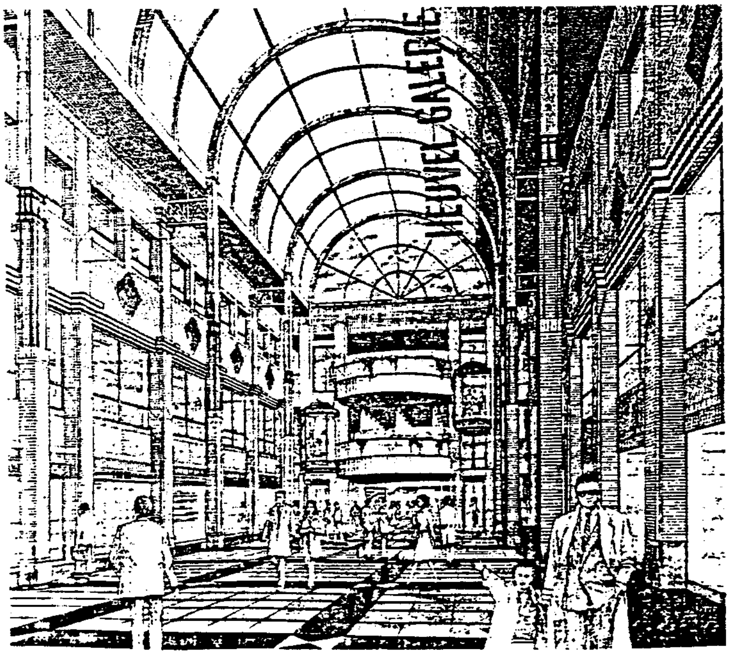

Figure 2 Shopping arcade in the Heuvelgalerie in Eindhoven

The Heuvelgalerie involves an extensive shopping mall. This 4-level complex incorporates a 220 metre long shopping arcade, interspersed with atria and dome-shaped roofs, approximately 20,000 $m2$ shops, a 8,600 $m2$ concert hall, 3,000 $m2$ restaurants, a 1,200 units car park, offices, and apartments.

It should be apparent that such a building is a highly complicated system. For instance, the manner in which air will flow depends on the external pressures on entrances and domes, temperature differences inside and with respect to outdoors, and impulses by the ventilation system. For this building ESP^R was used to make various predictions with respect to the indoor environment (Pernot and Hensen 1990).

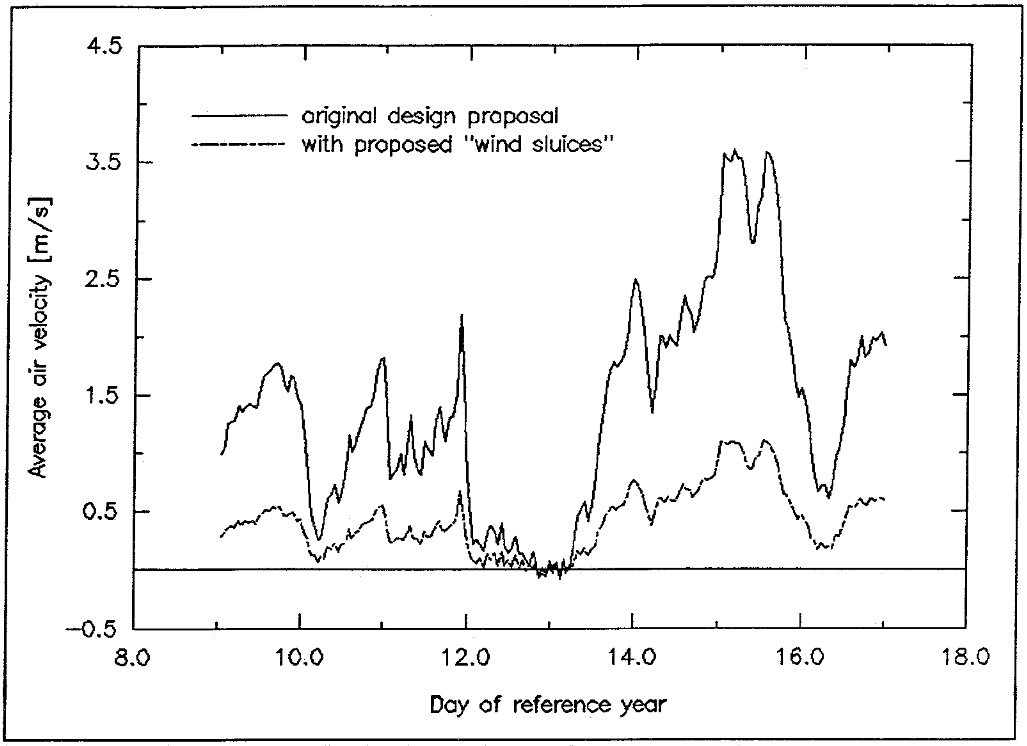

Figure 3 Predicted effect of proposed "wind sluice" to decrease the air velocities in the pedestrian entrance area; ie the passage connecting to the main square.

As an example, consider Figure 3 which shows results with respect to the air velocities which may be expected in the pedestrian entrance area. For commercial reasons, the architects and the developers want the entrance areas to be as open as possible. From the first results it was clear however that the original design proposal (incorporating air curtains for the main entrance) would lead to unacceptably high air velocities. One of the main conclusions was that additional air flow restrictions were necessary. For this it was suggested to apply double sets of sliding doors (wind sluices) at the "cafe" and "west" entrances, and to incorporate extra sliding doors + side hung doors at the main entrance. In case of severe wind, it should be possible to further restrict the (open) cross-section of the main entrance.

These are merely two examples, more or less demonstrating both ends of the spectrum of knowledge transfer / design decision support possibilities in the area of building energy use. Obviously there are various intermediate approaches; these often take the form of some simplified calculation method. The envisaged user profile usually shifts from more designer-like towards more specialist-like as the method shifts from design-aids towards the full simulation model.

Since buildings are complex mechanisms, involving phenomena such as transient conduction and air movement, there is a growing realisation that traditional design tools cannot cope with this complexity.

Particularly at the earlier stages of the design process, there is a need for rapid feedback on the cost and performance consequences of alternative design scenarios. The present system of specialist consultants, while adequate for the detailed design and final specification phases, fails to provide this immediate 'ad hoc' advice.

CONCLUSIONS AND FUTURE DIRECTIONS

It may be apparent that while development of sophisticated building performance evaluation tools as indicated above will comprise a valuable addition to the building engineer's toolkit, they also create new problems deriving from the conflict between the necessity for the tools to be powerful, comprehensive and according to first thermodynamic law principles to adequately represent the real world complexity while also being simple, straightforward and intuitive to facilitate user interaction. Such problems are not restricted to novice users but they apply to experienced users as well (Van Nes 1991).

As Clarke (1991) points out, the conflict between power and ease of use is further exaggerated by the divergence of the conceptual outlook of the design orientated program users and the technically orientated program developers. And to complete the confusion, there is the subtly different terminology of the various engineering professions. One - very promising - way to tackle these problems, is by utilisation of Knowledge Based System (KBS) and Human-Computer Interaction (HCI) techniques to create an Intelligent Front End (IFE).

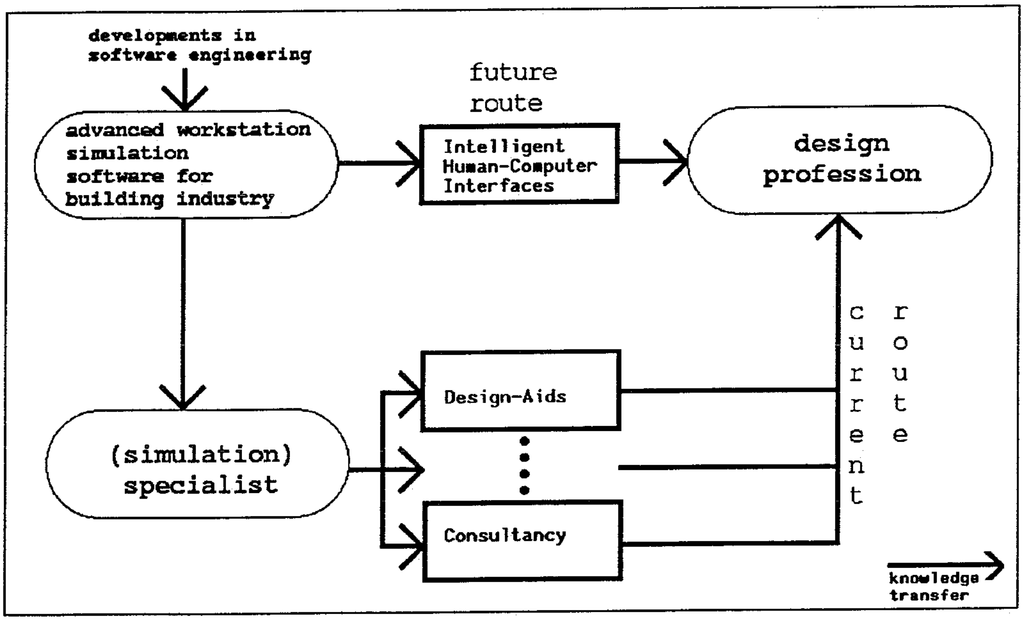

Figure 4 Current and future route of knowledge transfer / design decision support starting from simulation tools which treat the building and plant as an integrated, dynamic system.

Using these techniques it is possible to construct a user interface which incorporates a significant level of knowledge in relation to building description - in the face of real world uncertainty and realistic performance assessment methodologies. Such a system would direct a user's line of enquiry, allowing 'What do you suggest ?' and 'Why do you ask ?' type responses. It would also be expert enough to devise an appropriate performance assessment methodology and to coordinate model operation against this.

Using an IFE, the powerful simulation core may be invoked much earlier in the design process, because it is readily available to the designer. Obviously specialist consultancy will still be necessary, but this can be limited to the more common questions / problems.

This shift from the more traditional approach using design-aids and via specialist consultancy, towards future direct application of powerful simulation tools by the design profession, is indicated in Figure 4. This future kind of design decision support in the area of building energy and indoor climate thus derives its power from its simulation core and its ease of use from some intelligent interface. It is in this direction that we are currently orienting our research activities.

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