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PLANNED DEVELOPMENTS IN BUILDING ENERGY SIMULATION

J A Clarke, ABACUS CAD Unit, University of Strathclyde, UK.
Jeff Hirsch, Fred Winklemann, Fred Buhl & Ender Erdem, LBL, USA.

This paper summarises the deficiences of the current generation of energy modelling systems. A plan of work is then proposed which will lead to the creation of the mechanism by which these problems can be overcome and the next generation produced. Current developments in the UK and USA are described.

INTRODUCTION

Many developments are underway in the computer-aided building design field. As CAD systems possessing the drafting function proliferate, a demand is growing for advanced performance appraisal software. Designers will then come to rely on simulation as the means to test alternative design hypotheses throughout the design process and post occupancy. Indeed CAD system integration is perhaps the most effective mechanism for market penetration of advanced energy analysis systems. Also, as many energy sources become more expensive, and as conversion and management technologies become more complex, designers of the future will be required to focus more critically on the intimate relationship between design and performance. This will require a quantum jump in the capability and accuracy of the energy simulation techniques then on offer.

It is also likely that with the advent of powerful, integrated CAD systems, and considering the investment made in model creation and the related performance database, that the design profession will seek to refine the building model and database beyond the construction phase. One possible scenario is that a client of the future will expect delivery of a computer-based model and its related performance database, in addition to the product of the design, the building. The information regarding building performance is then readily available for inspection. And, of course, the model can be used at any time as the basis for trouble shooting exercises and retrofits.

Researchers developing building performance simulation techniques can no longer afford to work as independent groups creating non-interchangeable software. Some mechanism must be found to give all developers access to the developments of others whilst retaining the flexibility to tailor a simulation system to individual needs. This is the subject matter of this paper. Developments are proposed which seek to create and order the building blocks of energy simulation. Private and public sector organisations can then use this *Kernel* to construct customised simulation systems which embody an appropriate level of detail, offer wide ranging application potential and utilise the most up-to-date techniques.

DEVELOPMENTS TO DATE

One view of the evolution of building energy simulation models is summarised in table 1. Traditionally, designers have relied on a range of disparate calculation techniques to quantify building performance at the design stage. The professional handbooks abound with such techniques, regarded by many as the ultimate tools for design appraisal. This 1st generation ‘handbook’ approach - including computerised manual methods - is piecemeal, in that no coupling is evident between the various discrete calculations; in fact, the designer is asked to become the coupling mechanism. For example, a steady state U-value calculation may be invoked to quantify envelope heat loss, a look-up table may then be consulted to determine an allowance for zone solar gain, and a degree-day formalism may be relied on to achieve an estimate of long term energy requirement. The individual calculations are analytical, embodying many simplifying assumptions to permit their formulation in the first instance. The approach does not attempt to faithfully represent the actual energy and mass flow-paths which occur in real buildings. Instead the intention is to provide the designer with an indication of performance. Such methods are easy to apply but difficult to interpret since the designer is required to appreciate the application limits of each calculation type, taking into account the complex sub-system interactions by relying on her/his experience. This implies the need for expert knowledge on the part of the user. Also, since many of the real world flow-paths and interactions are degraded or ignored, the integrity and overall accuracy of the handbook method is low; for example, the commonly assumed steady-state, uni-directional wall heat flow rarely, if ever, occurs in the real world. And so, pursuant to the oil embargo of ’73, the modelling challenge of the past decade has been to raise simulation integrity by explicitly modelling the active flow-paths and the observable interactions.

In the mid-70's the so-called 2nd generation models began to emerge. Now the temporal aspect of the simulation problem began to receive attention, particularly in the case of long time constant elements such as multi-layered wall, roof and floor constructions. The underlying calculation methodology was still piecemeal and analytical in nature: for example, time or frequency domain response factors may be used to obtain the envelope's dynamic response to climatic stimulii, weighting factors or energy balance techniques may then be used to achieve zone response by invoking the superposition theorem, and the cooling and heating loads to result may be used as the basis for separate, steady-state design calculations addressing the building's systems and central plant. The approach is appropriate only if the system for simulation is linear and can be described mathematically by parameters which are time invariant. Modelling integrity remains low because of the inherent decoupling and the simplifying assumptions applied to the flow-paths. For example, the nature of any control link between the building and its plant, if included, will be treated in a rudimentary manner. And surface convective and radiative heat transfer coefficients are often prescribed and fixed so that no realistic treatment is applied to the important convective and long wave radiative processes.

In very recent times, 3rd generation models have begun to emerge. For the first time (in this application field), the simulation task is considered as a classical field problem in which the only true independent variables are the space dimensions and time. All other quantities (flux exchanges and variables of state) are entirely dependent and fully coupled across space and time. No single process can be solved independently and so simultaneous processig methods are required. Finite volume (or element) discretisation is preceded by the generation of conservation equations for each volume and for each property to be conserved - such as energy, mass or momentum. The overall equation set is typically a mix of partial and ordinary differential equations and algebraic expressions. The equations may well be non-linear, sometimes complex. Whole-system equation-sets are *stiff* and, when represented in matrix form, topologically sparse. Advanced numerical methods are therefore required to achieve efficient and accurate time-step integration. Third generation models are therefore suitable for complex transient problems, exhibiting weak and strong coupling. Combined heat and mass transfer has been addressed for the first time and there has been a distinct shift towards more appropriate user interfaces utilizing graphical I/O and the new processor/display technologies. Modelling integrity has been raised substantially so that the systems have become more predictive vis-a-vis reality, more generally applicable and, because of the improved interface, easier to use. However, an important problem confronting 3rd generation programs is that numerical representations of HVAC equipment requires knowledge of heat capacities, fluid heat transfer coefficients and component geometry. This data is generally unavailable or extremely difficult to obtain. A major reason that some 2nd generation models are in wide use is that they simulate a variety of building equipment in terms of quasi-steady-state performance curves, readily obtainable from manufacturers' data.

DEFICIENCES OF CONTEMPORARY MODELS

At the present time then, the extant systems for building energy simulation are a mix of 2nd and 3rd generation. These are the systems which, with continuing refinement over the next 5 years, will seek to replace the traditional, 1st generation techniques. Indeed a growing user community of practitioners, educationalists and researchers is currently struggling to find ways to cost-effectively apply these systems in practice. But what of 1990 and beyond? While this new technology offers sophisticated modelling capabilities, there are many deficiences which will restrict future refinements to satisfy the needs of an increasingly more demanding user base. For example any existing system will suffer to some extent from one or more of the following.

- The software structure is often extremely inflexible and unyielding. The program may have been conceived in a now outdated machine environment - possibly batch oriented with card input. This means that the structure is monolithic, imposing extreme management and updating difficulties.
- To date it has not been possible to formulate a common approach to the simulation problem. Funding policy and the ever present competition within and between the private and public sector has served only to stifle inter-organisation collaboration. The result is that each system has customised I/O procedures and unique internal structure. Physical models are different in each code, as are linking protocols, network representations, theoretical emphasis and so on. This situation is obviously divisive and generates little confidence in the developments taking place.
- Often system authors are energy specialists, but coding amateurs. The software structure is inelegant, with the application knowledge inextricably bound to the source code. Contemporary software engineering favours the

separation of the domain specific knowledge from the software. This is a fundamental prerequisite of expert system design which, if disregarded, can become a serious barrier to software evolution. For example, with existing systems it is often difficult to upgrade algorithms since this may require the detailed knowledge of data structures, internal memory and possible side effects of one change on the rest of the software package. More elaborate modifications, such as substituting one numerical integration scheme for another, are at present intractable problems.

- Many of the currently available systems are of unacceptably low integrity. The real world flow-paths have been oversimplified or omitted and simultaneity has not been addressed. An unsuspecting user is then left to struggle with the inadequacies of a model which has unacceptably degraded the all-important temporal and spatial couplings. These issues will certainly raise doubts about accuracy and flexibility and are the main focus in any validation exercise.
- And finally there exists no clear statement on long term development objectives and task sharing developments. In consequence many existing systems are not well tailored since each author organisation has been forced to address every element of the problem: I/O, heat transfer theory, database design and management, solution techniques, software structure, validation, documentation, etc. It is clear that no single organisation will possess the necessary expertise in all areas. Each system is then promoted in a manner which implicitly undermines the development effort expended on its contemporaries. This is clearly an intolerable situation and one which serves only to fragment an already small development community.

If the challenge is to overcome these problems, then the time is right to devise a plan of action which will allow effective community wide collaboration and lead to the next generation of building energy modelling systems. Table 1 also summarises the likely features of the next generation: full CAD system integration; increasingly sophisticated numerical methods; expert system interfaces; and an object-oriented software architecture. The adoption of such a modular approach will undoubtedly aid the process of collaborative software development, where different groups work to produce different but complementary object modules. It will also facilitate the later introduction of parallel processing in computer hardware and will ease the maintenance and updating tasks once a sizable system has been developed. The result will be a next generation architecture which will possess high integrity, be easy to use, and will facilitate effective but frugal energy management.

A WORK PLAN

It is now widely accepted by the leading building performance simulation groups in Europe and North America that the best way to proceed is to develop a flexible model construction system, which can then be used to build and test future modelling systems. Only in this way can we escape from the inflexibility of monolithic, single structure programs, and move instead towards an object oriented approach to model construction which encourages task sharing. To this end an international research project has been formulated. The intention is to develop a *Kernel* system comprised of three distinct elements as follows.

Software primitives

Many useful models and computational techniques already exist within contemporary modelling systems. And much additional software continues to emerge as existing codes are extended or new developments pursued. The first task is to divide the useful, existing software into small, logically independent object modules called 'software primitives', and to place them within a central, public domain library. Each library entry is then a small program or process which performs a single and dedicated task. The library entries are independent in the sense that each primitive has no knowledge of any overall data structure. The primitives obtain data and return results in a standard way, by invoking special primitives which fetch data from and return data to a central storage area. There is no attempt to prescribe an overall modelling methodology; instead the free evolution of useful *software tools* will be encouraged among those concerned with developments in building energy simulation. Naturally portability is a necessary attribute for all of these tools.

The primitives' library has different types of entries: first principle, conservation equation generators for building and system components; separate, self-contained algorithmic approaches; data manipulators; software development and management tools; validation primitives; and simulation support modules. These are the entities which are manipulated by the software harness detailed below. By accepting a high level of pluralism it is likely that a rich modelling base can be formed, entirely free of application assumptions. Note that many precedents already exist for such an approach; the NAG and SPSS libraries in the statistics field, GKS for computer graphics, the UNIX operating system and its software tools, and numerous mathematical and structural (finite element) libraries. Specifically the following tasks are planned.

- The required primitives will be identified and agreed upon.
- The standards for constructing a primitive will be considered and clearly defined.
- A proforma, or submittal form, will be drafted and tested to allow different groups to submit algorithms, theories and procedures for transformation into a useful primitive.
- A central body will be created to receive proformas, generate the corresponding software tools, and document and test the submitted primitives.
- Software will be created to allow the insertion of new primitives as free-standing entities.
- The publication of a related journal is also envisaged to inform the modelling community of the availability of new primitives as they emerge.

Each researcher can then make a contribution to emerging methods in energy simulation by offering up the knowledge required to generate a primitive. The best contributions then become more established through widespread use. For example, some contributions may focus on lumped representations - say polynomial curves representing the shortwave transmittance, absorptance and reflectance of a window system, or the part load performance curves of equipment. Other contributions may result in primitives which, instead, use Fresnel's equations to address window shortwave radiation response, or which generate state-space formulations, time-step by time-step, for items of plant. Or primitives might serve only to help validate other primitives when active in a simulation: performing energy balance at various locations for example, comparing the results from a numerical scheme with a known analytical solution, perform sensitivity studies, and so on. And yet others might act to impose empirical or measured data time-series on a simulation. Many of these functions are already active within existing programs and so could be made available in the proposed format without great effort. Finally, numerical integration techniques are available in models such as **AZTEC**, **ESP**, **DEROB**, **GEMS**, **HVACSIM**, **MITAS**, **SINDA**, **SPICE** and **TRNSYS** and in various math libraries such as **NAG** and **SLATEC** The best of these techniques can be extracted for inclusion in the software primitives library.

Software harness

The second element of the Kernel is the harness (or executive) which allows the extraction of primitives from the library according to some flow-graph template offered up by a user. Primitives are then combined into an actual modeling system. The harness consists of a *data manager* used to define and control data traffic among the primitives and a *simulation controller* to control the sequence in which the primitives (or clusters of primitives) are executed. Creation of a software harness is analogous to the development of an operating system such as UNIX where the problems of concurrent processes and communication among processes have already been addressed. The use of techniques from this field also facilitates a later introduction of parallel processing. It also permits the construction of *any* modelling approach, subject only to the availability of the necessary software primitive. From the establishment and integration of matrix equations representing energy and fluid flow within buildings and their systems, to more pragmatic models which rely on actual performance measurements or apply simplifications appropriate to the design problem in hand.

It is important to note that the software harness is for use by model developers not model users. It is an efficient way of building appropriate models which can be easily improved as the underlying techniques are refined. Users would continue to use program prescriptions, the only difference being that their architecture will be highly modular and so easy to change. The harness has the following support elements.

- Data management routines to control information flow among software primitives.
- Simulation control routines to receive the flow-graph template and to trigger the operational primitives.
- Test procedures to investigate harness performance at both the component and whole system level.

Consider the following example of the software harness and runtime control. In existing programs, the control flow and data flow between software modules are fixed. A typical algorithm might be represented by the flow-graph of figure 1, where the circled numbers indicate the sequence in which the modules are executed. By keeping this flow-graph information in a *template* that contains the sequencing of modules, it is possible to introduce a higher level of flexibility. Replacement of one or more modules by others can be accomodated simply by reconfiguring the template. Since the data flow to each software primitive is controlled by the data manager routines of the harness, the location of data is unimportant. It can be in memory, on a disk file, or at another node in a computer network. The algorithm of figure 1 might then be represented by the template of figure 2. The dashed lines indicate sub-networks. To modify program flow, a message system is used between the simulation controller and the active primitives or object modules. In such a system, a primitive can request that a new sub-network be followed, it can request a branch or loop to a new node in the network, or it can recursively call itself.

With this separation of data, primitives, and control, it is possible for each of these areas to evolve independently and be easily re-integrated for testing or general use. A complete modelling system can then be achieved by linking these elements as shown in figure 3.

Knowledge base

The third important element of the Kernel involves, firstly, the setting down of the rules which govern model construction and, secondly, model use in a design, educational or research context. This is the next essential step towards the so-called expert system in which the program must process a model of the user as well as simulation primitives (or a model of the process). Concerning model construction, it would seem appropriate to commence by setting down the rules employed by some of the contemporary programs as a first step template. Normal academic interchange would then serve to evolve these templates or to create completely different approaches. Each organisation/researcher can have their say, allowing the more effective templates to become prominent with time.

Model use is a different problem. A proper debate on the role of models in design is long overdue. The intention here is to explain how existing and planned energy simulation systems can best be used for performance assessment. This is the knowledge which is required by those future developers who will construct expert systems in this application area. Here the intention is *not* to develop decision-making software based on the latest Artificial Intelligence techniques, but to establish a number of assessment methodologies for each of the cost and performance attributes of interest. Specifically:

- By inviting inputs from the active developments groups, it should be possible to set down the software templates for the existing programs.
- National and/or international workshops would seem to be the appropriate mechanism to enable potential model users to voice their expectations of design appraisal by simulation.
- Additionally, the group of successful, seasoned users of existing software represents a source of knowledge that could be used for an expert system-based user interface concerned with knowledge solicitation and simulation coordination.

ADVANTAGES OF THE KERNEL APPROACH

The modular approach offered by the proposed Kernel provides a flexible framework for future model development, testing and management. The following list identifies some of the more important advantages.

No single organisation need be expert in all areas in order to formulate a whole-building model. On the other hand, anyone who wishes can undertake the development of either general or special purpose whole- or part-building models using the software primitives and the harness.
New capabilities, in the form of additional software primitives, can be added as they are researched and proven.
Modelling methods - detailed and general, micro and macro - can be mixed within one computational environment.
The building envelope, systems, plant and control action will be fully coupled. Alternatively, decoupling can be introduced at any interface to facilitate theoretical examination or model reduction.
Modelling systems based on the Kernel will be able to accomodate the different time constants possessed by the individual components active in any simulation, and it will be possible to adopt mixed and variable time-stepping schemes.

Mixed one, two, and three dimensional schemes will be possible for the case of transient conduction modelling since more than one primitive can exist for any function.
It will be possible to simulate any configuration, from a single zone through a multi-zone building, to a combined building and its services. That is, the Kernel is to be totally component based.
Simulations can be constrained to conform to innovatory control actions since new primitives can be added to influence problem formulation (at the dictates of some control signal) or to generate control equations which then participate in some simultaneous solution.
Any external database system could be used to supply the application data. In each case it will only be necessary to add new database driver primitive.

Many research activities will continue as before. The hope is that the Kernel will act to bring about resource sharing by making available the results of one group's labours to another group in the form of a software primitive. Individual groups will continue to evolve mathematical models of the components and sub-systems found in buildings; to establish and test solution techniques suitable for the integration of non-linear differential equations; to develop advanced man-machine interaction techniques and intelligent knowledge-based methods of use communication; and to formulate methodological templates which define a program's structure in terms of the many internal connections among its parts. These are the activities which the Kernel seeks to order and make available.

It should be emphasised that the Kernel developments do not attempt to define the R&D which should take place within the building energy simulation community. Research groups will continue to conduct fundamental studies into convective heat flow, unifying formalisms for building simulation, the transient behaviour of plant components and control systems, and so on. The contribution of the Kernel is to provide a collaborative framework for these developments by making available a number of essential software tools. In this way unnecessary duplication can be avoided and research efficiency improved.

CURRENT STATUS AND FUTURE DEVELOPMENTS

The first stage in the Kernel programme was to seek inter-group collaboration in principle so that the normal R&D process could continue in the context of some generally approved work plan. This has now been achieved in North America and the UK where most groups support the proposed developments.

In North America, Kernel developments have commenced with the issue of a Department of Energy Research Contract to Lawrence Berkeley Laboratory (1), with sub-contracts being placed with the National Bureau of Standards and the University of Wisconsin. To date several software primitives have been established and a prototypical harness is in operation. Also, to oversee Kernel developments, and to address the wider issues of building performance appraisal by simulation, a new organisation has been formed - the **I**nternational **B**uilding **P**erformance **S**imulation **A**ssociation or IBPSA (pronounced eye-bep-sa). The Charter statement and mission of this organisation are defined in detail elsewhere (2).

In the UK, developments have been slow to commence. What now seems likely is that the Science and Engineering Research Council and the Department of Energy, through the Energy Technology Support Unit, will together fund a *research club* of different UK groups acting towards a single end; the Kernel. Such a proposal is currently being formulated (3).

There can be few, if any, alternatives to the Kernel system approach. It offers the means by which state-of-the-art can be fostered by offering ease of integration. It is the essential ingredient in the next generation of computer model for the appraisal of building performance by simulation.

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