Validation of buildings and systems energy prediction using real measurements

J P Cockcroft

This paper looks at the requirements for validation of a model and at the techniques which can be used. The author reports on his own experience with instrumenting an office building in Glasgow, UK. The type of data required for validation is examined. Integration of building and systems modelling is discussed, and the requirements for this to occur in the future are examined.

computer-aided design, building design, energy

The modelling and simulation of physical systems using computers is a well established technique in many fields of advanced technology where the building of physical prototypes to evaluate every conceivable design strategy is impossible. Typically, these applications of computer modelling have been applied most extensively in the aerospace industries and in the design of large civil engineering structures, where the penalties of design error are considerable.

To provide the level of confidence essential to these applications, considerable effort is expended to ensure that the computer modelling techniques used are accurate, and will reproduce the results of instrumented model and full scale test bed cases. This validation process, in addition to ensuring the fidelity of the modelling techniques, also establishes the input data and justifies the assumptions that are inherent in any modelling process. Designers will then feel confident in applying simulation to design and produce real structures with a high probability that performance will be up to specification.

Traditionally, on the other hand, building design has been a matter of applying the results of previous experience to new projects. The most elaborate calculations involved rarely require more than a calculator, and the objective has been to achieve approximations sufficient to ensure adequate environmental conditions with plant capacities that are more than sufficient. A number of factors have come together which are bringing about changes in design approach.

Rising fuel prices have awakened building owners' interest in reducing running costs by tighter control of energy in buildings. This leads to a requirement for evaluation of alternative schemes using different fuel conversion devices and exploring various energy conservation and recovery possibilities. More complex building and systems design is needed to satisfy more demanding requirements from building owners, and the old manual techniques have, in a number of cases, proved inadequate, leading to buildings and systems whose performance falls short of expectations.

Computer modelling techniques for buildings are consequently enjoying a rapid uptake amongst the design professions. The need to validate these techniques is perceived as being less imperative for building design than it is for design of aircraft or suspension bridges and a number of reasons can be found for this.

First, the consequences of failure are not seen to be catastrophic. At worst, environmental conditions will not be achieved and fuel costs will be higher than anticipated. Remedial action rather than demolition would in all probability be applied to ensure at least that environmental conditions are adequate. The immediate pressures for commercial exploitation of newly developed software, by designers anxious to exploit the latest technology but not fully aware of the dangers of implicit trust in computer generated answers, lead to a view that adequate validation of computer modelling techniques is not essential.

Second, there is no doubt that the physics of thermal interactions in buildings is very complex, and there are uncertainties and variations in the properties of the fabric materials themselves. No modelling technique is capable of including all of these effects. The real skill in developing a modelling strategy is to include in sufficient detail those effects and phenomena that affect most significantly overall thermal performance, within acceptable contraints of computer capacity and costs.

Third, the actual process of validation requires the acquisition of data from measurements in real buildings. To carry this out effectively is expensive and time consuming, and consequently the data is often not sufficiently comprehensive to fully assess a complete modelling technique.

MODEL VALIDATION REQUIREMENTS

There are a number of requirements for computer modelling validation that any designer proposing to use a particular piece of software should ensure have been satisfied, or at least be aware of in terms of possible shortcomings as a result of incomplete validation.

Honeywell Control Systems Ltd (formerly with Building Services Research Unit, University of Glasgow, UK)

- *Comparison with real measurements:* it is important to distinguish between model validation and software validation. In the latter case one is ensuring that the mathematical processes incorporated into the design of the modelling technique are working correctly, and this may involve comparisons of results between different computer programs to determine consistency. While this is an essential part of program development, it is quite distinct from validation of modelling technique, which can only be done by comparison with the results of actual measurements.
- *Measured properties:* it is common for programmes of measurements to be carried out in buildings without a clear specification of comparison requirements. Computer programs can often predict values of for example, heat flow, which in practice are quite difficult to measure and are therefore frequently omitted from the instrumentation schedule. Often the only energy flows directly measured are fuel consumptions. These flows, while of immediate interest, may be several stages removed from the energy flows of interest for model validation: those supplied by systems to the building, and those interacting with the building fabric.

Comparisons between measured and computed thermal performance may therefore be limited to relatively few variables, often controlled variables or variables strongly influenced by controlled variables, whose values are less likely to deviate from computer prediction in any case. It is likely also that unmeasured properties will be adjusted to 'calibrate' the model to the measured data. This underlines the importance of comparison with more than one building, and of the advantages of comparison being carried out by someone other than the modelling program developer.

Good measurement programme planning should provide critical model testing, and also guide the program developer towards deficiencies and areas needing model improvement.

VALIDATION TECHNIQUES

Laboratory studies

Physical testing of individual components has a role to play in developing models by providing an understanding of physical processes and generating input data. There is less value in laboratory testing for validation of building models because the interactions between systems, buildings and weather cannot be fully realized.

Small plant systems however can often be tested quite thoroughly in the laboratory. Computer models of such systems can then be combined with a previously validated building model, and the interactions between buildings and systems studied using computer simulation with a high level of confidence in the results.

Special purpose building

An unoccupied building can be fully instrumented and very detailed studies carried out. Such studies can be used to test widely differing situations under carefully controlled conditions. The one criticism levelled at such exercises is that they produce atypical results that are difficult to relate to normal occupied buildings, although for model validation requirements this is of lesser importance. Studies of this sort are fairly uncommon because of the difficulty of obtaining vacant buildings for sufficiently long periods of time.

Instrumented occupied buildings

Instrumenting an occupied building, or incorporating instrumentation during construction of a building which will subsequently be occupied, is the most frequently used approach. This suffers from the disadvantage that detailed measurements in the occupied space are not possible, and the unpredictable nature of people has to be accounted for. However, the total cost of this type of exercise, particularly in a large building, is less than it would be if carried out in an unoccupied test site, mainly because there is no cost or rental for the site itself. This fact, coupled with the added benefit of apparent realism, tends to favour this method of obtaining measurements of full scale building thermal performance.

HOW MUCH VALIDATION?

Currently validation of computer programs tends to be carried out as an aid to their development, usually on a single set of data, and subsequent validations are seldom carried out unless under pressure from external sources. This pressure is now starting to develop as a result of the interest, shown by some countries, in using energy analysis computer programs as a means of developing national energy conservation codes of practice, or in using programs as part of the process of ensuring conformity with regulations. The extent to which such programs can be relied on to produce results that correspond with real building performance, will depend on the extent to which they have been validated against real buildings. It is not sufficient to merely compare total fuel consumption of buildings with computer predictions. Measures of building and systems performance should be included, and program improvements and refinements made in response to evidence of deficiencies. When results do diverge, there is then a means of determing the cause, and refinements are possible. In brief, therefore, validation is necessary to increase the credibility of thermal performance predictions. The range of buildings to be used should reflect the range of capabilities of computer programs, and should ensure exercising of the various prediction techniques.

INTERNATIONAL ENERGY AGENCY PROGRAMME

To strengthen co-operation in the vital area of energy policy, an Agreement on an International Energy Programme was formulated among a number of industrialized countries in November 1974. The IEA (International Energy Agency) was established as an autonomous body within the OECD (Organisation for Economic Co-operation and Development) to administer that agreement. Twenty-one countries are currently members of the IEA with the Commission of the European Communities participating under a special arrangement.

As one element of the International Energy Programme, the participants undertake co-operative activities in energy research, development, and demonstration. A number of new and improved energy technologies with the potential to make significant contributions to our energy needs were identified for collaborative efforts.

In one of these areas, energy conservation in buildings, the IEA is sponsoring various projects to improve the accuracy of prediction of energy use in buildings. This wo began in 1977 with comparisons between several computer programs for predicting energy usage in buildings. A hypothetical office building was selected as the basis for these comparisons. Widely varying outputs from the computer programs resulted, the causes for which could be identified as follows:

- Despite having a very detailed specification, describing the building, its materials of construction, internal gains and operational schedules, the scope for different interpretations of the presented data and terminology was surprising. The number of items of data omitted from the specification, particularly in relation to convection and radiation coefficients, was also a source of divergence between program results.
- Differences in modelling techniques, particularly in relation to thermal storage, were a further cause of divergence. To some extent, programs using similar techniques produced similar results.

Participants in this initial phase of the IEA program comparison exercise became increasingly aware of the need for a comparison with data obtained from measurements in a real building; otherwise there was no generally acceptable means of resolving the differences between programs which were attempting to model an identical building. To this end the Building Services Research Unit at Glasgow University put together a proposal to fully instrument a commercial office building.

There are obvious advantages in adopting an international approach to high cost ventures of this nature. Individual organizations cannot find sufficient funds to support projects on this scale, but can benefit equally from a cooperative funding arrangement, with the added benefit of the involvement of expert groups from other organizations and countries.

As an aid to the development of this project and to further investigate different programs' predictions, data obtained by the South Western Electricity Board from measurements in their Avonbank headquarters in Bristol was used in a second stage comparison exercise. Tighter definition of the building specification was achieved, and an attempt to include air-conditioning systems in the modelling process was made. Again there were divergences between programs, and also from the measured data:

- Modelling of air infiltration, and air movement between zones within a building are important effects which need more attention focused on them.
- Predictions of energy usage can be significantly affected by how thermal storage is modelled.
- It will not always be possible to estimate heat extraction rates from a space without some consideration of equipment used to achieve heat extraction. Latent cooling can occur at fan coil units even though there is no latent cooling requirement.

The study also underlined some important features of any computer program validation exercise:

- Measurements in a real building must be such as to yield data that can be compared with computer predictions. Otherwise a direct comparison can be difficult to achieve.
- Reliability of measurements must be high. A small quantity of missing data can greatly reduce the value of the remainder of a dataset.

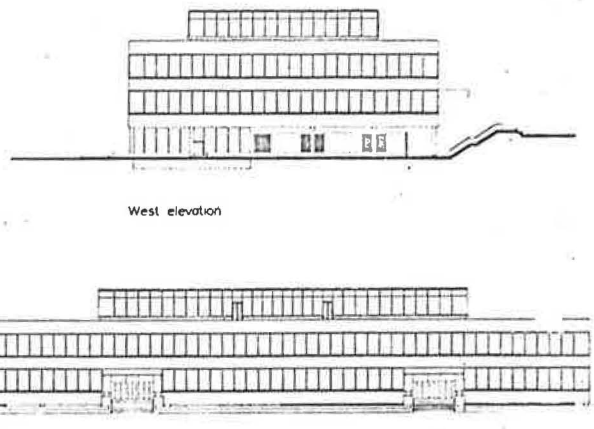

Figure 1. Collins' publishers office block

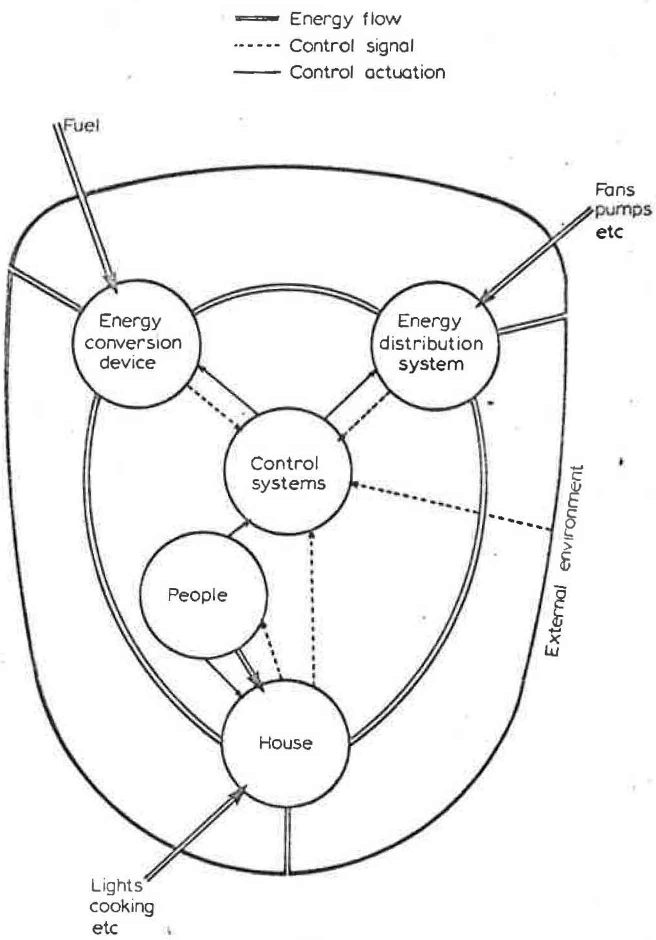

Figure 2. Physical systems defining general modelling requirements

- Terminology must be very precisely defined. Often the basis of comparison may be combinations of several elements to make up some energy transfer in a building. Unless this combination is clearly explained the wrong interpretation of requirements will be made.

GLASGOW COMMERCIAL BUILDING MONITORING PROJECT

This project is now underway at the Collins Publishers Office block near Glasgow (Figure 1) with participants from Australia, Belgium, Canada, Holland, Switzerland,

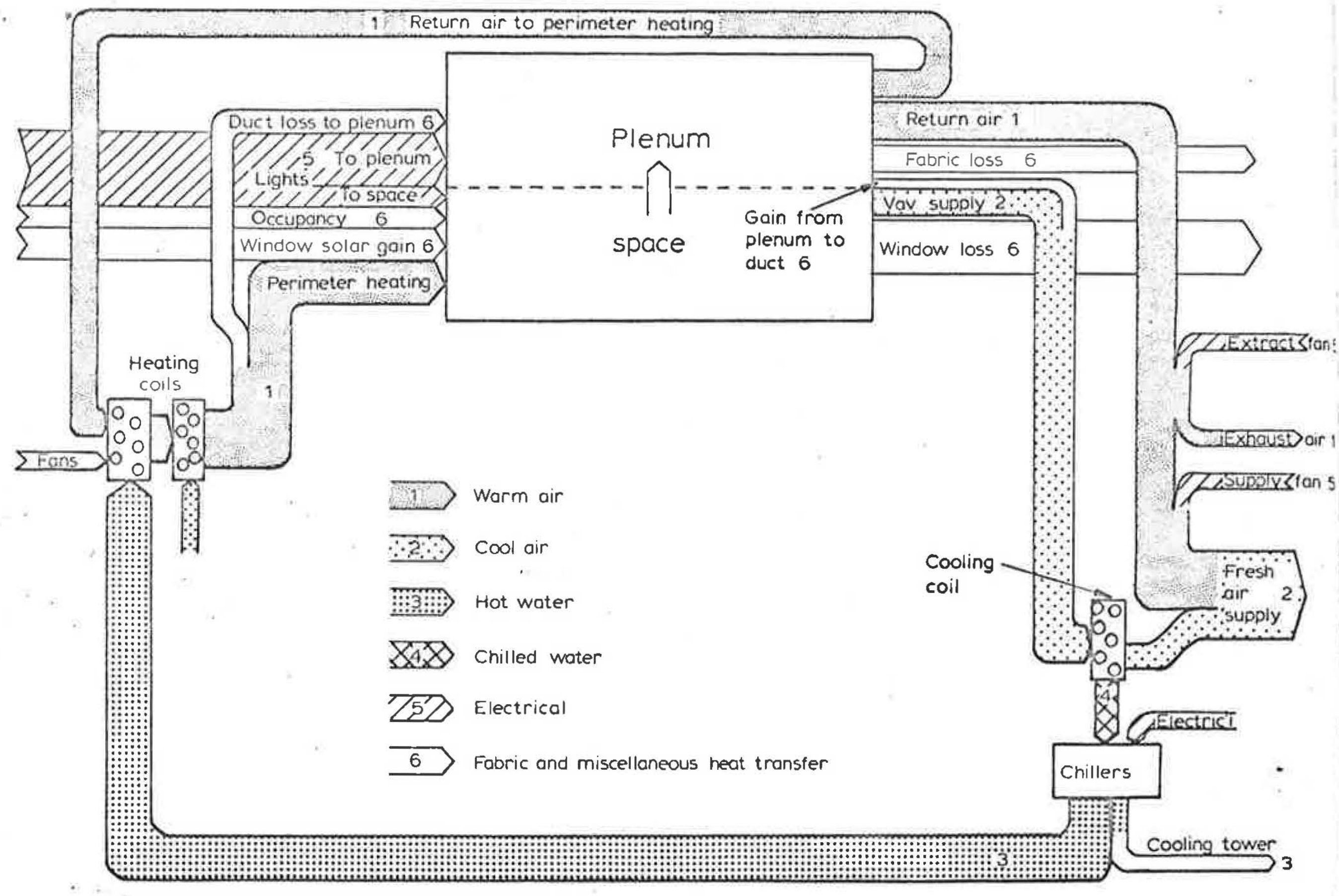

Figure 3. Energy balance in office block main VAV and perimeter heating systems only

USA and the UK. A very detailed schedule of instrumentation has been prepared, for measuring temperatures, air and water flow rates, electricity consumptions, fabric heat flows, infiltration, solar radiation and weather. Nearly 500 inputs to a data logging computer system will provide much better measurements of energy flows than were available for Avonbank. The basis for comparison will therefore be the real performance with less emphasis on comparison between programs than was the case with the previous studies. The lessons learnt from these studies have influenced the way data is being measured, and the amount, detail, and presentation of information to participants in the form of a building specification.

Computer predictions of building performance will be submitted on magnetic tape to an agreed format, and analysis and comparisons of these results will be possible without the need for manual transcription of the data. The measured data will ultimately be available, in the same format, to participants who wish to carry out their own further analyses.

Systems performance prediction

One important new aspect in the Glasgow project will be the studies of equipment performance. Some work was done on this for Avonbank, but the unusual three pipe system, the lack of good measurements, and the large discrepancies at fabric performance level, discouraged most participants from proceeding to model the Avonbank systems.

Analysis of the Collins building energy predictions will include comparisons carried out at several levels of thermal performance:

- fabric heat gain/loss and solar effects
- environmental conditions
- energy added or removed by air handling systems
- energy transferred between water and air systems
- performance of main systems components (chillers, etc)
- energy inputs to the building

Although there are many computer programs available for modelling and simulation of the dynamic thermal response of building fabric to variations in weather and internal loads, very few can treat the systems that maintain environmental conditions in buildings with the same degree of complexity. There is clearly considerable scope for development in this area. A large contribution to the efficiency of fuel utilization is made by these systems (see Figure 2), which include fuel conversion devices, energy distribution systems and control systems. The need to predict the performance of systems is essential to the evaluation of alternative energy handling schemes and improvements to existing plant combinations. What is required is an integrated energy systems approach, which will represent the interactions of systems with each other and with the building construction. Only with such a tool can one fully investigate modern control strategies and heat recovery possibilities. In addition to providing an assessment of fuel usage, such predictive facilities can be used to investigate control accuracy and stability – an increasingly important consideration for new systems and constructions.

There are a number of modelling requirements for systems that contrast sharply with the requirements for building modelling, and there is a need to assimilate these requirements together.

- *Complexity:* systems are complex to model even for small systems, eg house heating, requiring typically at least the same order of modelling complexity as the building model. Also, the dynamic time scale is much smaller, leading to an incompatibility between systems and building simulation.
- *Flow process modelling:* a major component in systems modelling is the need to include flow processes in the structure of the model. This applies mainly to air, water and refrigeration circuits which, in many modern systems, are continually varying in response to control systems actuation. Also, the ventilation and infiltration processes in a building have a significant effect on thermal performance and can have a big effect on how a building should be zoned, for example.

The above factors complicate systems modelling and can act as a deterrent to many analysts wishing to account for systems performance. However, the results of detailed systems modelling can yield significant rewards in terms of understanding complex dynamics, and gaining confidence in tight systems design for efficient energy usage by buildings.

The analysis of the Collins building systems (Figure 3) will bring the IEA participants to the point of discovering how well programs can predict actual energy inputs, and whether assessments of, for example, heat recovery possibilities, can be made reliably, and which techniques achieve the required results most effectively.

THE FUTURE

Even after techniques for effective evaluation of buildings and systems performance have been developed and adequately validated, there will remain two particular areas of difficulty that must be overcome before practical use of such facilities can become integrated into the building design process.

- *Systems specifications:* the need to consider buildings and systems together raises professional difficulties. The building structure and systems designers need to adopt an integrated approach to a complete building and systems specification, if maximum benefit is to be gained from a systems modelling capability.
- *Input data requirements:* it is a widely recognized difficulty that plant component manufacturers rarely specify operating characteristics of their equipment in a way that is suitable for modelling purposes. Often this results in the software developer having to provide this data or the programs only being usable by specialist personnel. The incentive for manufacturers to provide data compatible with modelling requirements may well come from an increased uptake of software by systems designers. This will encourage companies to provide the necessary information in an attempt to maintain their market shares.

Our expectations are that the Glasgow Collins project, and other related international ventures, will not just provide the means of improving the credibility of existing prediction techniques. As a result of the interest generated by such work, improved software, with integrated building and systems simulation, will be developed, and become available to meet the needs for more energy conscious building design in the eighties.