Procedures for Scaling and Replication by Simulation

P A Strachan[*]
ESRU, University of Strathclyde

The most effective way of establishing confidence in the ability of a simulation tool to model a particular component or system is to compare the predictions with measured data. These data can derive from experiments in test cells or monitored test buildings. In both cases, however, the performance cannot be directly translated to generalised conclusions because the conditions of the test are not representative of conditions within typical real buildings. A procedure has been developed using simulation which permits the scaling of performance of a building component on a test cell to the performance of the same component on a real building. It involves the selection of a reference building which is representative of a particular class of building and for which representative conditions of occupancy, infiltration, ventilation, control and climate are specified. It is believed that this procedure is more flexible and able to deal with complex interactions when compared with the alternative procedure which involves the extraction of performance characteristics from the experimental data and their application using a simplified design tool.

INTRODUCTION

The starting point for this paper is the problem of how to assess the performance of any building or plant feature (e.g. constructional element, control strategy, heater type...) in a range of building types and in different climatic regions. The most obvious technique is to monitor suitable buildings containing the feature of interest. However, apart from the difficulties in establishing a detailed monitoring scheme and in ensuring the information is representative (of a particular class of buildings and climate), it is difficult to disaggregate the performance of the feature of interest from the overall building response. This can be achieved by running side-by-side monitoring schemes, but in full-scale buildings it is difficult to ensure that all conditions (e.g. due to air infiltration) are identical for the two buildings.

More commonly, experiments are undertaken in test buildings or test cells in which conditions can be more closely controlled. In such cases it is necessary to extrapolate from the specific conditions of the test (which are usually not realistic in terms of occupancy, infiltration etc) to real building performance.

This paper discusses ways in which scaling and replication from test experiments can be tackled. A procedure is then described by which modelling can be used to predict real building performance, and an example is given of the evaluation of one particular building component, a conservatory (sunspace).

TECHNIQUES FOR SCALING

In the following, it is assumed that experiments have been undertaken on a test cell. The techniques and conclusions can equally be applied to monitored test buildings: these will perhaps have less detailed instrumentation, but on the other hand they are likely to be closer in terms of geometry and construction to conventional buildings.

There are three main routes by which the translation from test cell to real buildings can be effected:

- Based on knowledge of the likely physical behaviour of the component under test (e.g. a temperature- or climate-dependent property), modifications could be incorporated into the standard test procedures to ensure that such variation was accounted for. However, in practice it is difficult to include all important factors within a commercially viable test sequence.
- By undertaking parameter normalisation, the variation of parameters due to location and climate could be eliminated. The normalisation

---

[*] Energy Simulation Research Unit, Department of Mechanical Engineering, University of Strathclyde, 75 Montrose Street, Glasgow G1 1XJ, Scotland. Phone: +44 41 5524400 x3024, Fax: +44 41 5528513, email: paul@esru.strathclyde.ac.uk

can be effected by the use of empirical relationships or by the use of simulation programs to produce the normalisation factors (van Dijk 1993). The resulting normalised parameters can then be incorporated into simplified design tools for general building application, used for comparison with laboratory derived parameters, or used for prescriptive regulatory purposes. However, it is difficult with this technique to take into account many of the dominant dynamic effects that influence building performance e.g. in the analysis of overheating potential or the effect of lags due to storage in thermal mass elements. There are also difficulties in assessing utilisation; i.e. how much of the available energy can be used in a real situation when other factors such as occupancy and ventilation requirements need to be considered.

- Using detailed simulation programs which have been calibrated against measured performance in an experimental investigation. In the case of components which have an important dynamic response (such as passive solar components), this route is probably the only practical one for including the influences of occupancy, heating schedules, realistic air flow regimes etc. on component performance.

It is considered that the most flexible and accurate procedure is the use of dynamic simulation programs (although the other techniques may be useful in some contexts); this is now discussed in more detail.

MODEL CALIBRATION

Before any confident predictions can be made on how a particular building or plant feature will perform when integrated into a real building, it is necessary to start with a calibrated model (where the term 'model' refers to the simulation tool's representation of the feature). A calibrated model is one which has been shown to perform well against experiment under controlled conditions in a test cell or monitored building. In the following it is assumed that the feature of interest is a particular building component, but a similar strategy could also be applied to study a control strategy (e.g. to determine how successful a particular blind control strategy is in maintaining comfort levels in a room) or a plant component (e.g. to study the importance of the position of a heater in a room). There have been several recent developments in the area of model calibration. Most of these have been applied to cases where there are significant uncertainties in the model input data, resulting in discrepancies between model predictions and measured data.

As has been noted by many workers, calibrating a model can be problematic in that the user has to decide which of the inputs must be changed in order to reconcile measurements and predictions. There are two aspects to this problem. Firstly, the input parameter(s) that may be in error must be selected, or a deficiency in the simulation program must be isolated. Secondly, the modification(s) required to achieve a good fit must be calculated. The expertise of the user is a large factor in both cases.

This problem has been tackled in a number of ways: from manual, iterative, pragmatic intervention (Carabott 1989, Kaplan et al. 1990); through the production of a suite of informative graphical comparative displays (Bronson et al. 1992, Haberl et al. 1993) and the use of special tests and analysis procedures to isolate and compare individual energy flows (Subbarao 1989, Balcomb et al. 1993); to a technique for automatically adjusting user selected input parameters to reduce the discrepancy between measured and predicted data (Carroll et al. 1989, Carroll and Hitchcock 1993).

In the PASSYS project (Wouters and Vandaele 1993), a major European initiative in the field of passive solar systems, there has been a somewhat different emphasis in the calibration procedure. In this case, very detailed, controlled experiments were conducted on a number of passive solar components in outdoor test cells, involving a high degree of instrumentation. It was therefore possible to more closely identify the cause of a discrepancy between measurements and predictions, and therefore amend the input data or simulation program as appropriate. Modifications were only made if justified from the analysis. The techniques evolved in this project enabled a systematic approach to calibration in the selection and justification of the interventions to be made, either to the model of the system under study or to the program (Clarke et al. 1993). The process comprises some or all of the following steps:

- The use of sensor information - for example surface temperature and flux measurements - to isolate potential reasons for large residuals.
- Establishing, by sensitivity studies, the inputs or algorithmic adjustments that are significant in terms of the predicted performance characteristics.
- Establishing, by residuals analysis, the correlation between program inputs and the discrepancies between measured and predicted outputs.
- The application of identification techniques to determine appropriate values of 'lumped' model parameters to minimise residuals (Van Dijk 1991). For example, identification using measured data can extract the effective construction UA value for comparison with the

predicted value. If necessary, the program or its input can then be adjusted (assuming that the experiment has been suitably designed to minimise the standard errors associated with the identified value). Attempts have also been made within PASSYS to directly identify values of the input parameters which would minimise the residuals (Jensen 1993), but this technique is not yet proven.

At the end of the experimental phase of the work, a model of the building component of interest should exist which has been demonstrated to perform well over a representative operational range.

METHODOLOGY FOR SCALING AND REPLICATION

Once confidence in a program's ability to model the performance of the building component has been achieved, it can be used to scale the behaviour to real buildings and to undertake replicability studies by assuming alternative design/climate configurations. In this way modelling can be used to bridge the gap between the controlled environment of the test cell and the complex issues encountered in practice, where there will be interaction with occupancy, air flow patterns etc.

The methodology adopted for scaling can be briefly summarized as:

- Selecting a reference building design.
- Simulating this design with and without the application of the building component and its associated control.
- Analysing performance in terms of energy and comfort criteria.
- Incrementally changing the design parameters and repeating the simulations in order to determine optimum configurations.

Replication involves studying the impact of alternative building designs when placed in different climates. Clearly, a component (such as a passive solar component) that works well for one given design/climate combination may perform badly for another.

The above procedure involves 'extrapolation', i.e. extending beyond the proven limits of the application of the model. However, such a procedure is justifiable provided that:

- The experiments on the test cell are designed in such a way as to ensure that the building component is tested across its full operational range.
- The experimental uncertainties are minimised by ensuring that monitoring standards are high.
- That reasonable confidence can be extended regarding the program performance in areas other than those tested in the specific experiments on the building component, perhaps through previous validation/calibration/scaling studies. This risk is ameliorated to some extent since we are comparing the performance of the building with and without the building component of interest, so that it is the performance of the component itself which is dominant.

Selection of a Reference House Design

The design chosen for the scaling will depend on the application. It may be that the purpose is simply to determine how a particular component will perform on a particular building, which then becomes the "reference design".

To determine the impact of the building component in a more general way requires the choice of an acceptable reference construction that is representative of a particular class of building and which can be used to extract generalised conclusions regarding the potential performance characteristics of the proposed component.

The choice of reference design is particularly important because of the likelihood that the assessed benefit of the component will depend on the chosen design. Similarly the selection of representative occupancy and infiltration is likely to be critical in the determination of the benefits of the component. For example, the maximum potential energy savings of a particular component may have been determined from the test cell experiments, but it is only the introduction of realism, in the form of air flow regimes and occupancy schedules, that will permit the question of utilisation to be addressed and the calculation of real potential energy savings to be made.

Criteria for Selection of a Reference Building

Because of the importance of the building selected, it is suggested that selection criteria should be established. These could include such factors as:

- The most likely application area of the component. This will affect the type of building chosen (detached house, office etc.) and whether it is a new or existing building type.
- The building should be representative so that generalised conclusions on performance can be drawn. In particular, the building should be:
  - representative in its design, i.e. volumes, glazing areas, construction, etc., and
  - representative in its use, i.e. casual gains, occupancy schedules, infiltration levels, etc.

- The design should be indicative of an actual building rather than an artificial design. This has advantages in that there could be future checks on the adopted scaling procedure through the use of monitored data. Also, it would be easier to establish the model and make use of existing plans.
- It must be possible to fit the particular component under investigation in a sensible manner. Because simulations are undertaken on the selected building with and without the component under investigation (in order to compare the performance), the design must be one in which the building component can be easily incorporated without the necessity for a major redesign.
- The selected building must be fully specified in terms of the required input parameters of the simulation program used.

The Reference Climate

There are two possibilities for selecting a suitable climate: either the simulations could be carried out with the same climate as recorded for the test cell experiments, or a reference climate data set could be used. The first choice has the merit of ensuring that the conditions on the scaled house closely match the conditions during the experiment; the second choice would allow more representative climatic sequences to be investigated.

APPLICATION

Within the PASSYS project, the scaling methodology has been applied to date on two of the passive solar components which were experimentally investigated in the test cells. The first was a TIM (transparent insulation material) component consisting of a sandwich of 100mm thick polycarbonate honeycombs placed between two glazings in a timber frame. In this case, the objective of the scaling was to check the efficiency of the component when introduced into a particular building, a nursery in Southern Italy (Morgana et al. 1993). It was demonstrated that the performance of the TIM component predicted by the dynamic simulation program ESP-r (Clarke 1985) was in good agreement with the measured data (from experiments undertaken at the Italian test site in Catania). This gave some confidence that the 'calibrated' model could be used to determine the performance of the component in a real building. The nursery was modelled with some of the conventional glazing replaced by the TIM component, and with a realistic heating and occupancy regime. The heating load savings were calculated, and some parameter variations were carried out to determine the effectiveness of mass storage in conjunction with the TIM component.

The remainder of this section is concerned with a more general study that was carried out regarding the performance of a conservatory (sunspace) in the UK. In this case a commercially available conservatory was tested on the UK PASSYS test site in Glasgow, attached to a timber-frame south wall on one of the test cells. A detailed model of the test cell and conservatory was created with careful treatment of the time-varying solar radiation distribution. It was found that the predicted air temperatures (using ESP-r) in the conservatory closely corresponded with the measured air temperatures (Strachan and Baker 1992, Jensen 1993). The agreement was good enough to conclude that the model of the conservatory was 'calibrated' and suitable for scaling to determine performance on a real designs when subjected to realistic patterns of occupancy, climate and air flow.

The first step in the scaling exercise was to determine a suitable reference building. The Energy Technology Support Unit (ETSU) of the (then) UK Department of Energy considered that the most useful focus for the study would be new-build housing. A short-list of potential designs was drawn up against selection criteria such as those described previously. These ranged from major builders standard house designs through to houses studied within ETSU's Passive Solar Programme because they incorporated some novel passive solar design feature. In the end, the Linford House design was chosen. This is a direct gain passive solar detached house of conventional block and brick construction with a higher than average glazing area on the south facade. It was chosen for the following reasons:

- It is a conventional design which complies with recent regulations regarding thermal performance.
- The design is uncomplicated, with no unusual features, and is therefore relatively easy to model.
- The design had been used for previous studies.
- All the eight houses built to this design had been monitored at a basic level; one house was instrumented more fully.
- The fact that the house design is low-energy indicated that it would be comparatively easy to incorporate the conservatory in a 'best practice' design.

A detailed 14-zone model of the house was developed, with occupancy schedules and airflow networks incorporated that are representative of typical cases. In the results presented here, a 'light' occupancy schedule, typical of a working family was used. Gains were scheduled according to the house being unoccupied during working hours of weekdays, but fully occupied at weekends. Instead of assuming fixed air change rates in the simulations, a moderately tight leakage scheme was defined so that pressure and buoyancy-induced air flow was represented and modelled explicitly. This meant that zone infiltration rates and inter-zone air flows were calculated at each time-step as a function of the changing zone temperatures and wind-induced boundary surface pressures. Simulations then conducted with this model constituted the base case.

A single-glazed conservatory (as tested on the test cell) was then added to the building in accordance with what might be considered best practice. The conservatory had a 6.3m x 2.0m rectangular plan and fitted over the existing south-facing double-glazed patio door of the Linford house.

Following preliminary simulations, it was decided that the simulation strategy would be:

- To carry out a series of simulations with the base case which was the Linford House with no conservatory, and then with the house and conservatory with a range of modes of operation (buffer, various solar ventilation pre-heat strategies). These would be carried out using typical and design climate sequences.
- To select from these two or three variants of operational modes which would be used for more detailed study.
- For the selected variants, calculate energy savings over the whole heating season (in this study, energy use was the main performance parameter selected, but others could have been considered).
- Again, for these variants, undertake parametric variation, applying selected design changes to assess the optimal conditions for maximising the energy benefits of conservatories.

Results from the following operational modes are presented here:

- **Buffer Mode**. The model of the house and leakage distribution was unchanged except for the leakage path from the living room. It was found that adding the conservatory reduced ventilation in the living room below acceptable levels. The size of the opening to the conservatory was thus increased to give comfortable levels of ventilation.
- **SVPH Mode**. One mode modelled was simple Solar Ventilation Pre-Heat (SVPH) operation (with no complex ducting to permit targeting of the ventilation air). Here, air was ducted from the conservatory into the living room, with the rest of the house leakage unchanged. Results are presented for two cases: SVPH providing 0.5 ac/h for the living room and 0.5 ac/h for the whole house.

Simulations were initially conducted using the UK example year climate data set, Kew 1967 (52°N). Table 1 shows the predicted energy consumption for space heating for the whole house over an assumed heating season of October to April inclusive.

The next step was to investigate some of the numerous possible parametric variations and combinations of variations that could be made to the established model in order to optimise performance and to investigate alternative designs and strategies. One possible strategy for optimisation could be to:

- List all parametric changes which are likely to lead to significant changes in performance.
- Undertake a short period simulation of each parameter change to estimate its likely importance. A rigorous procedure could make use of differential sensitivity analysis in a similar manner to that employed in the design of the test cell experiments (Jensen 1993). This would result in a table of those parameters contributing most to changes in the selected output performance parameter.
- Select those factors contributing most to performance of the building component of interest.
- Carry out a series of simulations of all combinations of the selected parameters.

In the present study, however, it was considered that the parametric study should be restricted to a small set of design changes that were of particular interest to the funding bodies. The selected parameters included changing from a single glazed to double glazed conservatory, investigating the effect of heating the conservatory to determine how rapidly the energy benefits are lost when the conservatory is heated as a living space, changing the occupancy/heating schedule from intermittent to continuous, and investigating the effect of adding a conservatory to houses of the same geometry but with constructions typical of different house building periods. The results of these studies are reported in Baker et al. (1992).

Some replication studies were also carried out. The simulations were repeated with exactly the same building description, using climate data sets from two other, more northerly, locations, namely Eskdalemuir in Southern Scotland (55.3°N) and Lerwick in the Shetland Islands (60.1°N). Results for the heating season are given in Table 2, in terms of energy savings relative to the base case. Some caution should be exercised with these results: although the 1967 Kew data is known to be representative for that location, the climate year for the other locations may not be typical.

Table 1. Space Heating Requirements in kWh for the Linford House, Kew Climate

	Oct	Nov	Dec	Jan	Feb	Mar	Apr	Total
Base	530.6	1151.2	1680.9	1789.1	1421.6	1040.4	914.9	8528.8
Buffer	494.7	1139.1	1680.8	1780.9	1392.9	984.9	869.2	8342.4
SVPH(0.5 ac/h living room)	482.1	1090.5	1614.4	1706.5	1335.1	925.3	814.9	7968.8
SVPH(0.5 ac/h whole house)	485.1	1151.2	1695.7	1786.8	1388.2	946.4	817.9	8271.2

Table 2. Energy Savings in kWh for Different Climates Relative to Base Case

	Kew	Eskdalemuir	Lerwick
Buffer	197	131	182
SVPH(0.5ac/h living room)	560	833	1202
SVPH(0.5ac/h whole house)	258	374	804

However, this exercise gave a warning against such simple use of replication to other climates. With the same leakage distribution as used for the Kew location, the air flow rates through the house were found to be very high for the more northerly locations where wind speeds are significantly higher. For example, over the heating season, average wind speed for the Lerwick climate was $8.3m/s$, against $4.5m/s$ for the Kew climate. For a typical winter week in Lerwick, air change rates in the living room averaged $4ac/h$, with a peak of some $9ac/h$. In practice, it is likely that steps would be taken to improve sealing of the house to reduce this level of infiltration.

The last statement is important when considering how best to generalise this replication study. Replication should ideally take into account 'best practice' for the alternative house location and building type, with changes to the base description where necessary.

CONCLUSIONS

A procedure has been developed which permits the scaling of performance of a building component on a test cell to the performance of the same component on a real building. It involves the selection of a reference building which is representative of a particular class of building and for which representative conditions of occupancy, infiltration, ventilation, control and climate are specified. It is believed that this procedure is more flexible and able to deal with complex interactions when compared with the alternative procedure which involves the extraction of performance characteristics from the experimental data (e.g. heat loss coefficient, solar aperture, effective capacity, etc) and their application using a simplified design tool.

It should perhaps be emphasised that there is a significant difference between the scaling and replication procedures referred to in this paper and the parametric studies that have commonly been carried out in the past (e.g. ASHRAE 1989) which have the aim of generating correlations on overall building performance. In the present case, the starting point is measured data of the building component of interest mounted on a test cell. The simulation model is then proven, or calibrated, against the measured data to ensure that the simulation model can confidently be used to predict the performance of the building component. Scaling is then undertaken in order to discover how the component works when placed on a full scale building (in a relative way, by comparing performance with and without the component). Parametric studies are carried out to determine how the component performance can be optimised.

The following are the main conclusions from the application of scaling reported in this paper:

- The first requirement is that good agreement is obtained with the comparison of measured and predicted data across the full operational range of the component, i.e. a calibrated model is available.
- The choice of reference design and representative operational conditions is critical to the eventual conclusions of the study.
- Apparent potential gains calculated from the test cell experiments may be much reduced when the question of utilisation is introduced. This was found to be the case for the conservatory where solar gains are reduced in the presence of natural infiltration, and where they are often not in synchronisation with occupation of the house.

The eventual confirmation, or otherwise, of the reliability of the scaling and replication procedures is only likely to result from complex monitoring exercises on a whole house basis. This remains a task for the future.

REFERENCES

ASHRAE 1989 ASHRAE/IES Standard 90.1-1989 "Energy Efficient Design of New Buildings Except Low-Rise Residential Buildings", ASHRAE, Atlanta, Georgia.

Baker, P.H.; J.A. Clarke; A.G. Guy; P.G.T. Owens; K.A. Pearson; P.A. Strachan; and J.W. Twidell. 1992. "PASSYS II: Final Report of the UK Consortium." University of Strathclyde, Glasgow.

Balcomb, J.D.; J.D. Burch; and K. Subbarao. 1993. "Short-Term Energy Monitoring of Residences." *ASHRAE Transactions*, Denver (June).

Bronson, D.J.; S.B. Hinchey; J.S. Haberl; and D.L. O'Neal. 1992. "A Procedure for Calibrating the DOE-2 Simulation Program to Non-Weather-Dependent Measured Loads." *ASHRAE Transactions*, Paper AN-92-1-5, pp. 636-652.

Carabott, M. 1989. "Building Simulation Reconciliation using Empirical Data." *Proceedings of Building Simulation '89*, Vancouver, Canada.

Carroll, W.L.; B.E Birdsall; R.J. Hitchcock; and R.C. Kammerud R. 1989. "RESEM: An Evaluation Tool for Energy Retrofits in Institutional Buildings." *Proceedings of Building Simulation '89*, Vancouver, Canada.

Carroll W.L. and R.J. Hitchcock. 1993. "Tuning Simulated Building Descriptions to Match Actual Utility Data: Methods and Implementation." *ASHRAE Transactions*, Denver (June).

Clarke, J.A. 1985. *Energy Simulation in Building Design.* Adam Hilger Ltd, Bristol and Boston.

Clarke, J.A.; P.A. Strachan; and C. Pernot. 1993. "An Approach to the Calibration of Building Energy Simulation Models." *ASHRAE Transactions*, Denver (June).

Haberl, J.S.; D.J. Bronson; and D.L. O'Neal. 1993. "An Evaluation of the Impact of Using Measured Weather Data versus TMY Weather Data in a DOE-2 Simulation of an Existing Building in Central Texas." *ASHRAE Transactions*, Denver (June).

Jensen, S.O. (Ed.) 1993. "The PASSYS Project. Subgroup Model Validation and Development - Final Report, Parts I and II, 1986-1992." Commission of the European Communities, DGXII.

Kaplan, M.B.; J. McFerran; J. Jansen; and R. Pratt. 1990. "Reconciliation of a DOE2.1C Model with Monitored End-Use Data for a Small Office Building." *ASHRAE Transactions*, Paper AN-90-11-1, Vol. 96, Part 1, pp 981-993.

Morgana B.; R. Lo Cicero Vaina; F. Parrini; and S. Vitale. 1993. "Empirical Whole Model Validation and Application to a Real Building Case Study: a Transparently Insulated Concrete Wall." *Proc. 3rd European Conference on Architecture*, Florence, May 1993.

Subbarao, K.; J.D. Burch; and C.E. Hancock. 1989. "Building Energy Simulations for Design, Evaluation, Commissioning, Control and Diagnostics." *Proceedings of Building Simulation '89* Vancouver, Canada.

van Dijk H.A.L. (Ed.) 1993. "The PASSYS Project. Subgroup Test Methodology - Final Report, 1986-1992." Commission of the European Communities, DGXII.

Wouters, P. and L. Vandaele. (Eds.) 1993. "PASSYS Services." Commission of the European Communities, DGXII.

Acknowledgements: This work was undertaken with the financial support of the UK Department of Trade and Industry and DGXII of the Commission of European Communities. The cooperation of many PASSYS colleagues is greatly appreciated.