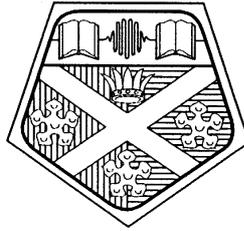


ESRU

Technical Report



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ESP-r: Summary of Validation Studies

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Introduction

ESP-r has been subjected to validation studies undertaken within many national and international validation projects, both by ESRU researchers and others. Projects in this report were undertaken by ESRU researchers unless otherwise indicated.

Comparison with Scottish test houses

- Two 3-bedroom houses in Livingston, Scotland were monitored (about 50 sensors plus climate data) in summer free-floating conditions. One was unoccupied, the other occupied. Predictions of air and surface temperatures showed good agreement with measurements in the unoccupied house. There was high uncertainty in infiltration rates which were only spot measured.
- ref: Clarke J A and Forrest I, 'Validation of ESP against Test Houses', ABACUS Occasional Paper No 61, 1978.
- ref: Clarke J A, Energy Implications in Building Design: A Thermal Simulation Design Model, Proc 3rd Int. Symp. Use of Computers for Environmental Engineering related to Buildings, Banff, Canada, pp3-20, 1978.

IEA Annex 1 (1977-80)

- This was an inter-model comparison of 19 different computer programs, including ESP-r, used to simulate the thermal load and energy requirements of commercial buildings. It was the first major international exercise of the type. Although predictions showed wide variations (typically to within $\pm 25\%$ in daily values and $\pm 30\%$ in peak load), there were useful lessons regarding modelling methodology and the level of detail required in the building specification. One of the buildings, the Avonbank building in Bristol was monitored (although not by project participants). Accuracy of model inputs was suspect, so no firm conclusions could be drawn.
- ref: Oscar Faber and Partners, IEA Annex 1 Computer Modelling of Building Performance: Results and Analyses of Avonbank Simulation, Oscar Faber and Partners, St Albans, UK, 1980.
- ref: US Dept of Energy, IEA Annex 1: Comparison of Load Determination Methodologies for Building Analysis Programs, DOE/CE/20184-1, US Dept Energy, Washington DC, 1981.

IEA Annex 4 (1979-82)

- Comparison of predicted with measured data from a commercial office building (Collins Publishers Headquarters) in Glasgow. The building was an open-plan air-conditioned (VAV system), monitored with over 500 sensors including automatic tracer gas for infiltration measurements. This was the first major empirical validation exercise, extending over 4.5 years. Nine simulation programs including ESP-r were involved in the study. Agreement was better between programs than between predicted and measured data. Problems in specification and in measurement data were identified. The importance of duct heat transfers, inter-zone airflow and the performance of systems and control in practice were also identified. There were many useful lessons concerned with difficulty of empirical validation on real buildings, but the Annex concluded that because of uncertainties in input data, results could not be used for validation of simulation models.

- ref: Glasgow Commercial Building Monitoring Project: Final Report, IEA Annex 4, Building Research Establishment, Garston, Watford, ISBN 085125 070X, May 1984.

IEA Task 8

- ESP-r was compared with 10 other programs against test cell data gathered at the Passive Solar Test Facility of the National Research Council of Canada. ESP-r predictions were within 8% of measured heating energy consumption over a 2-week period. Local overheating maximum temperatures were within 1°C in most cases. In addition, 5 detailed simulation programs were compared for a series of benchmark tests based on residential buildings (precursor to BESTEST - see below). A "reasonably narrow set of ranges in loads and peak temperatures was obtained".
- ref: Morck OC (ed), Simulation Model Validation using Test Cell Data, Thermal Insulation Laboratory, Technical University of Denmark, June 1986.
- ref: Bloomfield DP, Test Cases for Evaluating Building Thermal Prediction Programs, BEPAC Research Report, 1990.

IEA Annex 10 (1984-86)

- Inter-model comparison of HVAC system simulation programs. This IEA Annex had 2 aims: firstly, to develop a database of component models for air-conditioning and hydronic heating systems; secondly, to undertake simulation exercises on realistic configurations to demonstrate simulation program capabilities. No comparisons were made with measured data, although simulation exercises were based on actual systems. Many programs and studies were involved in the Annex, but typically only 3 or 4 programs for any particular study. Results reported varied in detail. One example is of boiler modelling. Results from 6 models (including ESP-r) gave annual energy consumption within 2.8% of each other, and similar trends were observed for changes to boiler configuration.
- ref: McLean D J and Clarke J A, 'Results of the Collins Building VAV Air Conditioning Simulation', IEA Annex 10 Interim Report, Apr 1985.
- ref: Lebrun J and Liebecq G, Annex 10 System Simulation Synthesis Report, University of Liege, Report No. AN10 881020-RF, 1988.
- ref: Morant M-A, Annex 10 System Simulation: The La Chaumiere exercises. Report No AN10 860327 - 01, 1986.

Comparison with Australian test houses

- This was an early comparison of measured and predicted data, for two houses in Australia, one in Townsville (elevated and free-running), the other in Melbourne (heated). The Melbourne house simulation was reasonable compared with the measured data, but the Townsville house gave poor agreement, thought to be due to uncertainties in the modelling of the ventilation.
- ref: Williamson T, 'The Goodness of Fit between ESP Predictions and Monitored Data from Two Australian Test Houses', ABACUS Occasional Paper, University of Strathclyde, 1984 (1986?).

Comparison with DOE2.1C

- Study undertaken by Fred Buhl.
- ref: Buhl F, 'Comparison of ESP and DOE2.1C, LBL Technical Report, Berkeley CA, 1986.

EC Study: various analytical tests

- This study was undertaken by EEC experts as part of a selection process for the European reference model in the area of passive design. Dupagne 1983 reported a quasi-theoretical solution for the response of a 1m test cube to a step change in outdoor temperature; ESP-r predictions of internal temperature closely followed the calculated response.
- ref: Archard P and Gicquel R (eds), 'Basic Principles and Concepts for Passive Solar Architecture', European Passive Solar Handbook, CEC, 1987.
- ref: Dupagne A, Comparison of Passive Solar Design Methods within EEC Program, Proc Conf on Design Methods for Passive Solar Buildings, UK ISES, Section 1, pp1-7, 1983.

SERC (now EPSRC) validation project (completed 1988)

- This was a large project involving 3 programs: ESP-r, HTB2 and SERI-RES, undertaken by the Universities of De Montford (then Leicester Polytechnic) and Nottingham, the Rutherford Appleton Laboratory and the Building Research Establishment. Validation work included review of theory (focussing on each algorithm and its implementation), analytical validation (solar processing, conduction, convective exchange, view factor calculation and internal longwave exchange), sensitivity analyses and a review of available test data sets.
- ref: Building Research Establishment/Science and Engineering Research Council, An Investigation into Analytical and Empirical Validation Techniques for Dynamic Thermal Models of Buildings, Vols 1-6, BRE, 1988.

Applicability Study I

- This 7 person-year research project was funded by the Energy Technology Support Unit of the UK Department of Energy as part of the Passive Solar Programme. It was undertaken by De Montfort University, with BRE as the major sub-contractor. The project focussed on inter-program comparisons between ESP-r, HTB2 and SERI-RES for passive solar houses. Results indicated that the 3 programs predict similar trends for energy use as geometry, construction type, heating system, thermostat set-point, window type and window orientation are varied. For double glazing or better, the programs predicted annual energy savings to be made by varying window area, orientation and type to be within a resolution of $\pm 7\%$. Algorithms describing internal heat transfer coefficients and the windows were identified to be primarily responsible for inter-program variability.
- ref: Lomas KJ, Applicability Study I: Executive Summary, ETSU Report S1213, 1992.

IEA Annex 21 (1988-93)

A comprehensive study concerned with analytical validation, inter-model comparisons (BESTEST) and empirical validation based on data from test rooms. ESP-r simulations were undertaken by ESRU (empirical validation) and De Montfort University (other validation studies).

- a) Empirical data from small well-controlled and monitored outdoor test rooms were compared with predictions from 17 different programs. Predictions and measurements were made of total energy consumption, maximum and minimum temperatures, vertical solar radiation and hourly temperature profiles. ESP-r predicted within the error bands of measurement for vertical irradiance and maximum and minimum temperatures, but underpredicted for heating energy consumption. Although some programs predicted energy consumption within the error band assigned to measurements, most programs underpredicted. Some causes suggested for this included heater dynamics/interaction with internal convective heat transfer, underestimation of edge losses in the test cell and non-uniform room air temperature. Sensitivity studies in this study (and others) indicated, for such test rooms, the importance of internal convection coefficients. This topic has now been addressed in ESP-r (Beausoleil-Morrison I, *The Adaptive Coupling of Heat and Air Flow Modelling Within Dynamic Whole-Building Simulation*, PhD Thesis, University of Strathclyde, 2000).
 - ref: Lomas K J, Eppel H, Martin C and Bloomfield D, *Empirical Validation of Thermal Building Simulation Programs using Test Room Data*, IEA Annex 21/Task 12 Co-operative Project, Final Report, Vols 1,2 and 3, Sept 1994.
- b) BESTEST: An inter-model comparison exercise of passive solar spaces. The work included a diagnostic method, based on incremental changes to a base case model, as well as comparisons between predictions from a number of detailed public domain programs from the US and Europe (qualification tests). One of the BESTEST diagnostics identified a problem in ESP-r with internal solar absorptance. Although this had already been identified and corrected, it showed the ability of BESTEST to identify potential sources of program error. In the qualification tests, ESP-r predicted relatively low annual heating loads for some tests. Sensitivity studies showed that the differences with other programs are largely a result of different algorithms for calculating internal surface convection coefficients. Since no definitive algorithms exist, ESP-r results were used in setting reference ranges for the qualification tests.
 - ref: Judkoff R and Neymark J, *IEA Building Energy Simulation Test (BESTEST) and Diagnostic Method*, IEA Annex 21/Task 12 Co-operative Project, Final Report, Feb 1995.
- c) Benchmarks for Commercial Buildings: This study was an inter-model comparison with 6 programs modelling a simple module of a commercial building in various configurations. Output parameters were annual heating and cooling, hourly integrated peak heating and cooling, peak room air temperatures, and heat losses for windows, exterior walls and ventilation. For annual and peak heating, ESP-r gave approximately 20% smaller values than the mean of all programs. For the majority of other parameters, ESP-r was close to the mean of predictions from all programs.
 - ref: Haapala T, Kalerna T and Kataja S (eds), *Energy Analysis Test for Commercial Buildings (Commercial Benchmarks)*, IEA Annex 21/Task 12 Co-operative Project, Report 101, Tampere, Finland, 1995.

- d) Analytical testing. Analytical tests were applied to ESP-r and SERI-RES (using simple zone models) to test for steady state and dynamic conduction, the incidence of direct solar radiation on external surfaces of arbitrary orientation, and the transmission of direct radiation through simple glazing systems. ESP-r calculated energy consumption of unventilated buildings in the steady state correctly, and the worst error in external heat flux due to a step change in temperature was 1.0% in the dynamic response tests. Small errors appeared in ventilated buildings due to ESP-r not taking account of variation of air density with temperature for calculating ventilation heat loss. Good accuracy in calculating solar position and incident direct radiation was reported. Errors up to 0.02 in transmission coefficient (only at high incidence angles) were found, resulting from ESP-r's interpolation algorithm.
- ref: Martin CJ, Seale CF and Eppel H, Analytical Testing of Detailed Thermal Simulation Programs, Building Environmental Performance '94, University of York, ppS-27-32, April 1994.

EC PASSYS project (1986-93)

- PASSYS was an extensive project involving teams from a number of EC countries, including ESRU. The focus was on developing outdoor test cell facilities, with model validation forming a major component of the work. The Model Validation and Development subgroup built on previous work to develop a validation methodology comprising literature review, code checking, sensitivity studies, inter-model comparison, analytical validation and empirical validation. This methodology was applied to ESP-r.
- Phase I. Validation studies were undertaken by teams throughout Europe studying individual processes and their implementation within ESP-r: they involved review of algorithms, code checking, inter-model comparison, analytical validation and sensitivity studies and limited process-level experiments. For example, in the case of internal long-wave exchange, the work built upon the BRE/SERC study referred to above. It included a review of different theoretical methods for calculating internal long-wave exchange, analytical tests, sensitivity studies, and an empirical side-by-side experiment. For external longwave processes, the literature review resulted in the implementation of the Berdahl and Martin algorithm in ESP-r.
- Phase II. Empirical whole-model validation based on the PASSYS test cells located at 14 test sites in 11 countries throughout Europe. These unoccupied room-sized test cells provided a realistically-sized test environment. However, because of the large thickness of insulation, 2-D and 3-D conduction was found to be important and data from a calibration wall was used to calibrate the ESP-r model. Passive solar components tested included a reference component (double glazed window in insulated wall), the reference component with added mass, a conservatory, transparent insulation, different glazing types, a Trombe wall. Work focussed on developing the methodology for such tests in terms of design of experiments, high levels of instrumentation, quality control on data, and production of high quality data sets. It included uncertainty analysis on measured and predicted data, and residuals analysis (to attempt to explain the causes for differences between measured and predicted data). As an example, in the case of a conservatory experiment of a 15 day test with the conservatory in buffer mode, the mean value of the residuals between measurements and ESP-r predictions for conservatory air temperature was 0.56°C.

- ref: Strachan P, Model Validation using the PASSYS Test Cells, Building and Environment, Vol 28 No 2, pp153-165, 1993.
- ref: Jensen SO (ed), Validation of Building Energy Simulation Programs, Part I and II, Research Report PASSYS Subgroup Model Validation and Development, CEC, Brussels, EUR 15115 EN, 1993.
- ref: Jensen SO, Empirical Whole Model Validation Case Study: the PASSYS Reference Wall, Building Simulation '93, Adelaide, Australia, pp335-341, 1993.

Comparison of Duct System Computer Models

- This project focussed on the selection of public domain computer modelling software for simulating the complex behaviour of ducted air distribution systems used for space conditioning in residential and small commercial buildings. Five programs were selected and subjected to a series of analytical evaluations (3 duct-system-only and one integrated system). Of these, 3 programs, including ESP-r operated by the Florida Solar Energy Center (FSEC), passed the criteria set. For the various tests, ESP-r showed agreement varying from acceptable to excellent; the worst discrepancy observed was 6%.
- The 3 programs were then used in whole building simulations in inter-comparison mode, with simulations undertaken by ESRU and analysis by FSEC. ESP-r air flows and pressures were very well predicted for each simulation; however, some problems were reported regarding predictions of energy penalties and delivery and distribution efficiencies. The authors also remarked on the difficulty of ensuring input equivalencing for such complex inter-model comparisons.
- ref: Gu L, Cummings J E, Swami M V, Fairey P W and Awwad S, Comparison of Duct System Computer Models that could provide input to the Thermal Distribution Standard Method of Test, FSEC-CR-929-96, Ashrae Project 852-RP, 1996.

BRE/EdF validation project: EMC test cells

- Empirical validation study undertaken by BRE and De Montfort University, based on data from the Energy Monitoring Company test cells, with 4 simulation programs used: Apache, Clim2000, ESP-r and SERI-RES. Although ESP-r predictions were slightly closer to measured data than other programs, analysis showed problems with modelling of heater dynamics and with the internal convective heat transfer coefficients. Stratification in the rooms was not modelled.
- ref: Bloomfield D, Candau Y, Dalicieux P, Dellile S, Hammond S, Lomas KJ, Martin C, Parand F, Patronis J and Ramdani N, New Techniques for Validating Building Energy Simulation Programs, Building Simulation '95, Madison, Wisconsin, USA, pp596-603.

BRE/EdF Empirical Validation Study: BRE Office

- The study involved a comparison of the monitored performance of an office on the BRE site in Garston, Watford against predictions made by several French (CA-SIS and CLIM2000) and UK (Apache, 3TC and ESP-r) programs. ESP-r simulations were undertaken by BRE. The study was conducted in several phases, in the first of which the modellers had no knowledge of the measured building performance. Two separate studies were conducted, both of a pair of unheated offices. There were no window blinds in the operation in the first stage; in the second stage a blind was added to one of the pair of office rooms.

- Uncertainties in input values were used to produce prediction error bars for the room temperatures in the no-blinds case, with the width of the band varying from approximately ± 2 to $\pm 4^\circ\text{C}$. Errors observed lay within these error bands. Good agreement among program predictions and measured data was obtained. For the second study, ESP-r predicted a maximum temperature difference between rooms with and without blinds of 2.1°C (measured 3.1°C) and a mean difference of 0.4°C (measured 0.3°C). Uncertainties in internal convective heat transfer coefficients were shown to make the largest contribution to the overall error band.
- ref: Bloomfield D, BRE Office Empirical Validation Study, Dec'99. Report Number v2-breoff-5a, BRE, Watford, UK.

BRE/EdF Empirical Validation Study: BRE House

- The study involved a comparison of the monitored performance of a house on the BRE site in Garston, Watford against predictions made by several French (CA-SIS and CLIM2000) and UK (Apache, 3TC and ESP-r) programs. ESP-r simulations were undertaken by BRE; again there was a blind validation first stage plus several sensitivity studies.
- Overheating produced by the combination of casual gains and solar radiation was reproduced well, with close agreement between measured and predicted peak temperatures. Cooling performance was also well represented, suggesting that thermal and heat loss effects are represented in the correct ratios. However, there were clear differences between program predictions for whole house energy consumption. Of interest is that in some cases, energy consumptions in the upstairs and downstairs zones were acceptable only due to fortuitous cancellations of errors occurring in the two zones, and that cancellation also occurred between errors on successive days. For example, ESP-r overpredicted whole house consumption by 9%; however, downstairs consumption was underpredicted by 4% and (the smaller) upstairs consumption was overpredicted by 44%. The cause is likely to be due to incorrect modelling of infiltration and air movement in the house, but as only whole house infiltration was measured, this could not be confirmed.
- ref: Bloomfield D, BRE House Empirical Validation Study, Dec'99. Report Number v2-bre18a, BRE, Watford, UK.

BRE/EdF Empirical Validation Study: Lisses House

- The study involved a comparison of the monitored performance of a the Valériane house at Lisses in France against predictions made by French (CLIM2000) and UK (Apache, 3TC and ESP-r) programs. ESP-r simulations were undertaken by BRE; again there was a blind validation first stage, plus several sensitivity studies.
- Comparison of whole-house energy consumption over the complete experimental period (more than two winter months) revealed errors ranging from -4% to +26%. Agreement was considered quite reasonable, but again disaggregated figures for upper and lower floors gave less satisfactory agreement; so processes connecting upstairs and downstairs zones are not so well modelled. A detailed sensitivity analysis indicated an uncertainty band of approximately $\pm 12\%$. All programs predicted values outside these ranges when results from individual phases and zones were considered.
- ref: Bloomfield D, Lisses House Empirical Validation Study, Dec'99. Report Number v2-brelisses-3a, BRE, Watford, UK.

Daylighting study

- A study was carried out by the Fraunhofer Institute in Freiburg, Germany, involving the prediction of daylight distribution. Six methods were compared with a reference case. ESP-r performed very well for the office space, but a recommendation was made that ground daylight coefficients would improve ESP-r's predictions for certain more complex building geometries.
- ref: Reinhart C F and Herkel S, An Evaluation of Radiance based Simulations of Annual Indoor Illuminance Distributions due to Daylight, Building Simulation '99, Kyoto, Japan, Sept 1999.

Validation as part of PhD theses:

- Essam Aasem: Analytical validation of an individual plant component (oil-filled radiator) and a plant network and inter-model comparison of a cooling coil model.
 - ref: Aasem E O, Practical simulation of buildings and air-conditioning systems in the transient domain, PhD Thesis, University of Strathclyde, 1993.
- Jan Hensen: Analytical testing on a network airflow model, inter-model comparison of a boiler model and an empirical validation of a radiator.
 - ref: Hensen J L M, On the thermal interaction of building structure and heating and ventilating system', Doctoral dissertation Eindhoven University of Technology, 1991.
- Nick Kelly: Analytical and inter-model comparisons for ESP-r's electrical power flow model.
 - ref: Kelly N J, Towards a design environment for building-integrated energy systems: the integration of electrical power flow modelling with building simulation, PhD Thesis, University of Strathclyde, 1998.
- John MacQueen: Analytical validation of building and plant-side controllers, inter-model comparisons of building-side, plant-side and global controllers and an empirical validation of the control of a AHU chiller.
 - MacQueen J, The modelling and simulation of energy management control systems, PhD Thesis, University of Strathclyde, 1997.
- Abdul Nakhi: Analytical, inter-model and empirical validation of adaptive gridding; inter-model and empirical validation of variable thermo-physical properties; analytical test of combined heat and moisture transfer.
 - ref: Nakhi A E, Adaptive construction modelling within whole building dynamic simulation, PhD Thesis, University of Strathclyde, 1995.
- Cezar Negrao: Analytical validation for 2-D flow in a duct and inter-model comparison for natural (2-D and 3-D) and forced (2-D) ventilation.
 - ref: Negrao C O R, Conflation of computational fluid dynamics and building thermal simulation, PhD Thesis, University of Strathclyde, 1995.
- Ian Beausoleil-Morrison: Analytic test and (qualitative) comparison against empirical data of an adaptive convection algorithm. Inter-program comparisons, sensitivity studies and comparison with empirical data of the implementation of the zero-equation turbulence model and alternative wall functions in the CFD domain.
 - ref: Beausoleil-Morrison I, The Adaptive Coupling of Heat and Air Flow Modelling within Dynamic Whole-Building Simulation, PhD Thesis, University of Strathclyde, 2000.