Project Summary Report

EBC

Energy in Buildings and Communities Programme

EBC Annex 43

Testing and Validation of Building Energy Simulation Tools Systems

Ron Judkoff

EBC

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Project Summary Report

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About EBC

International Energy Agency

The International Energy Agency (IEA) was established in 1974 within the framework of the Organisation for Economic Co-operation and Development (OECD) to implement an international energy programme. A basic aim of the IEA is to foster co-operation among the twenty-eight IEA participating countries and to increase energy security through energy conservation, development of alternative energy sources and energy research, development and demonstration (RD&D).

Energy in Buildings and Communities

The IEA co-ordinates research and development in a number of areas related to energy. The mission of one of those areas, the EBC - Energy in Buildings and Communities Programme, is to develop and facilitate the integration of technologies and processes for energy efficiency and conservation into healthy, low emission, and sustainable buildings and communities, through innovation and research. (Until March 2013, the EBC Programme was known as the Energy in Buildings and Community Systems Programme, ECBCS.)
The research and development strategies of the EBC Programme are derived from research drivers, national programmes within IEA countries, and the IEA Future Buildings Forum Think Tank Workshop, held in April 2013. The R&D strategies represent a collective input of the Executive Committee members to exploit technological opportunities to save energy in the buildings sector, and to remove technical obstacles to market penetration of new energy conservation technologies. The R&D strategies apply to residential, commercial, office buildings and community systems, and will impact the building industry in five focus areas of R&D activities:

- Integrated planning and building design
- Building energy systems
- Building envelope
- Community scale methods
- Real building energy use

The Executive Committee

Overall control of the program is maintained by an Executive Committee, which not only monitors existing projects but also identifies new areas where collaborative effort may be beneficial. To date the following projects have been initiated by the executive committee on Energy Conservation in Buildings and Community Systems (completed projects are identified in grey):

Annex 1:	Load Energy Determination of Buildings
Annex 2:	Ekistics and Advanced Community Energy Systems
Annex 3:	Energy Conservation in Residential Buildings
Annex 4:	Glasgow Commercial Building Monitoring
Annex 5:	Air Infiltration and Ventilation Centre
Annex 6:	Energy Systems and Design of Communities
Annex 7:	Local Government Energy Planning
Annex 8:	Inhabitants Behaviour with Regard to Ventilation
Annex 9:	Minimum Ventilation Rates
Annex 10:	Building HVAC System Simulation
Annex 11:	Energy Auditing
Annex 12:	Windows and Fenestration
Annex 13:	Energy Management in Hospitals
Annex 14:	Condensation and Energy
Annex 15:	Energy Efficiency in Schools
Annex 16:	BEMS 1- User Interfaces and System Integration
Annex 17:	BEMS 2- Evaluation and Emulation Techniques
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Annex 29:	Daylight in Buildings
Annex 30:	Bringing Simulation to Application
Annex 31:	Energy-Related Environmental Impact of Buildings
Annex 32:	Integral Building Envelope Performance Assessment
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Annex 35:	Design of Energy Efficient Hybrid Ventilation (HYBVENT)
Annex 36:	Retrofitting of Educational Buildings
Annex 37:	Low Exergy Systems for Heating and Cooling of Buildings (LowEx)
Annex 38:	Solar Sustainable Housing
Annex 39:	High Performance Insulation Systems
Annex 40:	Building Commissioning to Improve Energy Performance
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Working Group - Energy Efficiency in Educational Buildings
Working Group - Indicators of Energy Efficiency in Cold Climate Buildings
Working Group - Annex 36 Extension: The Energy Concept Adviser

General Information

Project leader: **Ron Judkoff, National Renewable Energy Lab (NREL), USA**
Project duration: **2003- 2007**
Further information: **www.iea-ebc.org**

Innovative low-energy buildings use energy-efficiency techniques and renewable energy technologies that frequently come with a higher construction cost, usually justified by estimated energy savings and reduction in CO_2 emissions. These estimates are often evaluated using complex building energy simulation tools, therefore it is very important to assure their reliability and accuracy. Robustness and fidelity improvements in simulation models have increased the building design professionals' level of the confidence in the use of these complex models.

The purpose of **EBC project 'Annex 43: Testing and Validation of Building Energy Simulation Tools'** was to developed software quality assurance for complex building energy analysis tools and engineering models that can be used to evaluate the performance of innovative low-energy buildings.

The main goal of this project was to create and make widely available a comprehensive and integrated suite of IEA Building Energy Simulation Test (BESTEST) cases for evaluating, diagnosing, and correcting building energy simulation software. The validation tests validated starting with simple cases and complexity was added systematically so there was a clear diagnostic path for analyzing model to data and model to model differences. Tests addressed modelling of the building thermal fabric and systems in the context of solar and low energy buildings, especially focused on:

- ground-coupled floor slab heat transfer models,
- multi-zone non-airflow and air flow models,
- solar gain models implemented in building energy simulation programs including the models for glazing units and windows with and without shading devices,
- models of different HVAC mechanical equipment components such as a chillers, cooling coils, condensing boilers and heating coils,
- heat transfer, ventilation flow rates, cavity air and surface temperatures and solar protection effect and interaction with building services systems for buildings with Double Skin Facades (DSF).

Over the four-year field trial effort, there were several revisions to the BESTEST specifications and subsequent re-executions of the computer simulations. This iterative process led to the refining of the new BESTEST cases, and the results of the tests led to improving and debugging of the simulation models.

The project's activities included also:

- maintaining and expanding as appropriate analytical solutions for building energy analysis tool evaluation,

Participating Countries:

Australia
Belgium
Canada
Denmark
France
Germany
Ireland
Japan
Netherlands
Sweden
Switzerland
United Kingdom
USA

Target Audiences

The audience for the results of the project is building energy simulation tool developers, and codes and standards organizations that need methods for certifying software. However, tool users, such as architects, engineers, energy consultants, product manufacturers, and building owners and managers, are the ultimate beneficiaries of the research.

- creating and making widely available high quality empirical validation data sets, including detailed and unambiguous documentation of the input data required for validating software, for a selected number of representative design conditions.

This work improved software tools for evaluating the impacts of energy efficiency and solar energy technologies commonly applied in buildings. Twenty four computer models shown in Table 1 were tested. Field trials for the new test procedures identified 106 results disagreements, leading to 80 software fixes, including both model and documentation improvements.

Table 1 Models tested during the project.

Model Tested	Participating Country
BASECALC	Canada
BSim	Denmark
CODYRUN	France
COMFIE	France
COMIS 3.2	Japan
DOE-2.1E	Switzerland
EES	Belgium
EnergyPlus	Switzerland
EnergyPlus	USA
ESP-r	United Kingdom
ESP-r/BASESIMP	Canada
FLUENT*	Kuwait
HELIOS	Switzerland
HTB2	United Kingdom
IDA-ICE	Sweden
IDA-ICE	Switzerland
KoZiBu	France
MATLAB*	Ireland
MATLAB-Simulink	Germany
SUNREL-GC/GHT	USA
TRNSYS-TUD	Germany
TRNSYS-16*	USA
TRNSYS-16	Belgium
VA114	Netherlands
VA114/ISO-13370	Netherlands
VentSim	Japan

Project Outcomes

Project leader: Ron Judkoff, National Renewable Energy Lab (NREL), USA
Project duration: 2003- 2007
Further information: www.iea-ebc.org

Introduction

Architects and engineers rely on building energy simulation tools. Accuracy improvements in simulation models have increased the confidence of building design professionals in the use of these complex models. The mission of the **EBC project 'Annex 43: Testing and Validation of Building Energy Simulation Tools'** was to developed software quality assurance for complex building energy analysis tools and engineering models that can be used to evaluate the performance of innovative low-energy buildings. The project's activities included developing comparative, analytical verification and empirical validation test methods for evaluating, diagnosing and correcting errors in building energy simulation software.

Project Overview

This project undertook research to develop a comprehensive and integrated suite of building energy analysis tool tests. The goals of the project were:

- create and make widely available a comprehensive and integrated suite of IEA Building Energy Simulation Test (BESTEST) cases for evaluating, diagnosing, and correcting building energy simulation software. Tests addressed modelling of the building thermal fabric and building mechanical equipment systems in the context of solar and low energy buildings,
- maintain and expand as appropriate analytical solutions for building energy analysis tool evaluation,
- create and make widely available high quality empirical validation data sets, including detailed and unambiguous documentation of the input data required for validating software, for a selected number of representative design conditions.

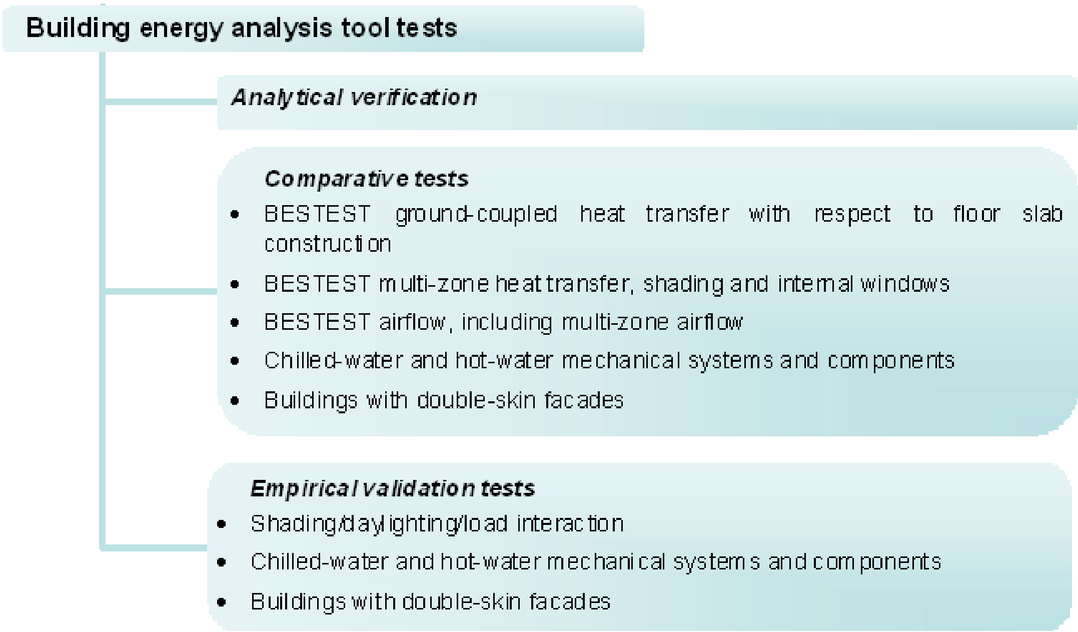
This project investigated the availability and accuracy of building energy analysis tools and engineering models to evaluate the performance of solar and low-energy buildings. However to be useful in a practical sense such tools must also be capable of modelling conventional buildings. The scope of the project was limited to building energy simulation tools, including emerging modular type tools, and to widely used solar and low-energy design concepts. Activities of the project included development of analytical, comparative and empirical methods for evaluating, diagnosing, and correcting errors in building energy simulation software.

Figure 1 shows the building energy analysis tool tests investigated in this project. These methods provided for quality assurance of software, and some of the methods were enacted by codes and standards bodies to certify software used for showing compliance to building energy standards.

Advantages of comparative tests include ease of testing many parameters, and that simple building descriptions may be used. However the major disadvantage is lack of any truth standard for cases where analytical solutions are not possible. In empirical validation, software is compared with carefully obtained experimental data. The advantage of empirical tests is that true validation of the models may be accomplished within the uncertainty of the experimental data. The disadvantages are that gathering high quality experimental data is expensive and time consuming, making it difficult to test the individual effects of many parameters.

Within the comparative test cases, analytical verification tests for evaluating basic heat transfer and mathematical processes in building energy analysis tools were included where possible. Analytical verification tests are comparisons with closed-form analytical solutions or with generally accepted numerical solutions performed outside of the environment of whole-building energy simulation software.

Figure 1 Building energy analysis tool tests.



Ground Coupling Tests

Ground-coupled heat transfer is a complex phenomenon that involves three-dimensional (3-D) thermal conduction, moisture transport, long time constants, and the heat storage properties of the ground. Based on simulations by National Renewable Energy Laboratory (NREL) typical slab-on-grade floor heat loss can range from 15% to 45% (Neymark J., Judkoff R., 2008) of the annual heating load. This result depends on a wide variety of parameters, including climate, above-grade thermal properties of the building, presence of slab and/or perimeter insulation, and the ground heat transfer model used for the calculation. Estimates of the range of disagreement among models used for calculating uninsulated slab-on-grade heat transfer were 25% to 60% (Neymark J., Judkoff R., 2008) or higher for simplified models versus detailed models, depending on the models being compared, building construction characteristics, and climate.

The objective of these in-depth test cases was to determine the causes for disagreements among detailed ground heat transfer model results found in preliminary test cases developed during Solar, Heating and Cooling Programme (SHC) Task 22 on Building Energy Analysis Tools: Analyzing Solar and Low-Energy Buildings (www.iea-shc.org/task22). The cases were divided into three series. The first series of test cases were for checking proper implementation of detailed 3-D numerical ground heat transfer models run independently of whole-building simulations. They included a steady-state 3-D analytical verification test case, and two other idealized steady-state and periodically-varying comparative test cases. The less idealized two other series of cases compared ground heat transfer models integrated with whole-building simulations to the independent numerical models.

The conceptual schematic diagram of a steady-state comparative test base case including boundary conditions and soil dimensions is shown in Figure 2.

Parametric variations in the cases included:

- periodic ground surface temperature variation (versus steady-state),
- floor slab aspect ratio,
- slab size,

Project Outcomes

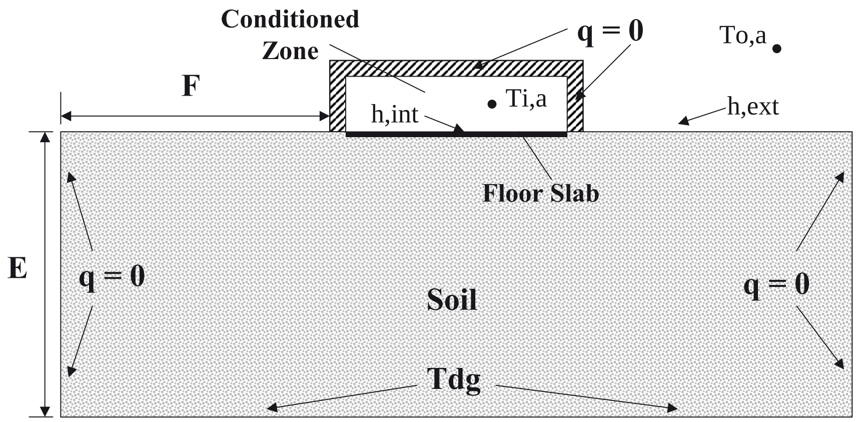


Figure 2 Conceptual schematic diagram of a steady-state comparative test base case including boundary conditions and soil dimensions.

- deep ground temperature depth, and
- interior and exterior convective coefficients (realistic versus high values to test the effect of surface temperature uniformity).

A set of idealized in-depth diagnostic test cases for use in validating ground-coupled floor slab heat transfer models were reported. These test cases represented an extension to IEA BESTEST, which originally focused on testing and validation of building thermal fabric models, but addressed only cursorily the modelling of heat transfer between the building and the ground.

Field trials of the new IEA BESTEST cases were conducted with a number of detailed state-of-the-art numerical models and state-of-the art whole-building energy simulation programs, which contained a variety of ground-coupled heat transfer models from around the world. The field-trial process was iterative in that executing the simulations led to refinement of the BESTEST cases, and the results of the tests led to improving and debugging the ground-coupled heat transfer models.

An important achievement of this project was the development of a formal methodology to facilitate using and verifying numerical models to develop quasi-analytical solutions. This allows for greatly enhanced diagnostic capability when comparing results of other simplified and mid-level-detailed modeling methods that are typically used with whole-building energy simulation programs, because the range of disagreement among quasi-analytical solutions is typically much narrower than the range of disagreement among simulation results that may be applying other modeling methods. This also allows quasi 16 analytical solutions to be developed for more realistic (less constrained) cases than exact analytical solutions allow. The methodology applies to both the development of the test cases as well as to implementation of the numerical models. The work resulted in diagnosis of 24 software issues resulting in 19 improvements to 7 of the simulation models, including:

- EnergyPlus
- ESP-r/BASESIMP
- BASECALC
- SUNREL-GC
- TRNSYS-GC
- •VA114, and
- DIT's model executed within MATLAB.

The detailed 3-D numerical-methods models of TRNSYS-GC, FLUENT, and MATLAB are able to produce results in agreement within 1% for the analytical solution case, and within 4% of each other for the remaining cases. These models provided a secondary numerical mathematical truth standard for the other cases.

Multi-Zone and Air Flow Tests

These cases tests were carried out to assess the ability of programs to:

- correctly keep account of inter-zonal conduction heat transfer,
- account for multi-zone shading by a single shading object and self-shading of the building by zones that shade other zones, and
- model internal windows between zones.

The IEA BESTEST cases were included:

- an in-depth analytical verification test case for multi-zone conduction and diagnostic comparative test cases for multi-zone shading and internal window models, and
- analytical verification test cases for airflow models, including tests for the effects of natural ventilation, buoyancy, wind driven, and temperature difference driven flows, and the effects of mechanical fan driven flows.

The shading and internal window test cases diagnosed 48 modelling issues related to conduction, shading, and internal windows and resulted in 32 improvements to 6 of the simulation programs including:

- CODYRUN
- EnergyPlus
- ESP-r
- HTB-2
- TRNSYS-TUD, and
- VA114.

For the multi-zone conduction case, all but one of the tested simulation programs agreed within 0.3% of the analytical solution. For the shading cases, results indicated the programs were properly accounting for multi-zone and building-self shading after a number of disagreements were diagnosed and fixed, and that shading models for both direct beam and diffuse radiation were working in a multi-zone context. The improved shading diagnostics for the revised cases allowed identification of software errors that reduced ranges of disagreement to about one third of the disagreement range evident at the beginning of the project. For the internal window cases, agreement among results also improved substantially as a result of model improvements during the project.

IEA BESTEST has been extended to include analytical verification test cases for airflow models, including tests for the effects of natural ventilation, buoyancy, wind driven, and temperature difference driven flows, and the effects of mechanical fan driven flows. Analytical solutions given in the final report provide a mathematical truth standard for the test cases. This project has resulted in diagnosis of 1 modeling issues related to an input error in VentSim, which was corrected.

Figure 3 EMPA Test Cells.

Shading / Daylighting / Load Interaction Tests

The purpose of this project was to create data sets for use when evaluating the accuracies of models for glazing units and windows with and without shading devices. Program outputs were compared with experiments performed at two research facilities designed for these types of studies:

- an outdoor test cell located on the Swiss Federal Laboratories for Materials Testing and Research (EMPA) in Duebendorf, Switzerland, shown in Figure 3.

Project Outcomes

Figure 4 ERS Test Rooms.

- Energy Resource Station (ERS) located in Ankeny, Iowa USA. The test rooms are shown in Figure 4.

Prior to the solar gain experiments, a preliminary exercise was performed to identify the most accurate tilted surface radiation model in each program. A series of experiments was then carried out in outdoor test cell in the EMPA to evaluate solar gain models in building energy simulation programs starting with the simplest case and increasing in complexity with each experiment. Increasing the com¬plexities of subsequent experiments allowed for careful assessments and diagnoses of the results. This experiment was simulated by seven building energy simulation programs, including:

- HELIOS
- EnergyPlus
- DOE-2.1E
- ESP-r
- TRNSYS-TUD
- IDA-ICE, and
- TRNSYS-ULg.

As a result of this work so far, several program errors and deficiencies in the programs have been identified with respect to solar radiation, glazing, shading, and surface heat transfer. This project resulted in diagnosis of 14 modelling issues, resulting in 14 improvements to 5 of the simulation programs including: HELIOS XP, EnergyPlus, ESP-r, TRNSYS-TUD and IDA-ICE. Overall uncertainty in various input parameters causes roughly ±3% uncertainty in simulated cooling load results.

Two additional experiments were performed at the ERS. For these studies, various windows and interior and exterior shading combinations were tested to evaluate daylighting algorithms and the associated interactions in building energy simulation tools and subsidiary software. Analyses were then performed to assess the overall performance of the programs. For this study, two building energy simulation programs were used, including: EnergyPlus and DOE-2.1E. Various parameters were compared at the zone level, including: reheat coil power, airflow rate, air temperatures, daylight illuminance at the reference points, and light power.

Conclusions are that overall predictions for daylighting performance were within acceptable ranges, and that uncertainty in the ERS – a real building – is greater than in a controlled laboratory experiment.

Mechanical Equipment and Control Strategies Tests

Empirical validation test cases were developed to test models related to hydronic mechanical system equipment and controls. Empirical data for both the hot-water and the chilled-water systems were obtained from several experiments conducted at the Energy Resource Station (ERS).

The models of different HVAC mechanical equipment components were developed with the help of EES (Engineering Equation Solver). This modelling tool allows an equation-based approach i.e. each component is modelled by a set of equations which describe the main physical processes/peculiarities inherent to the component. The proposed models involved a limited number of parameters, all of them having a physical meaning. The models do not require exhaustive information, such as the exact geometry of the component.

The prepared report aimed at showing how the parameters of the models could be identified using only manufacturer submittal or commissioning information. For each model, the distinction was made between the input variables, the output variables and the parameters. This modular approach made easier the inter-connection between the different models: the outputs of one model become the inputs of another model.
The proposed models are very suitable for modelling global HVAC systems (an entire cooling or heating plant, which can be connected to a building model) in order to compute primary energy consumption. For each HVAC component, a description of the model was first given. The parameters identification method was then presented. A short analysis of the simulation results was finally carried out for each model. The investigated HVAC components were:

- chiller (hermetic scroll compressor),
- cooling coil,
- condensing boiler, and
- heating coil.

After several iterations of test specification and model improvements, model agreement with experimental data was greatly improved. This project resulted in diagnosis of 10 modeling issues related to hydronic equipment and controls, resulting in 8 improvements to 3 of the simulation programs including: TRNSYS-TUD, VA114, and U. Liège's model executed within EES.

Building Double Façade Tests

The main objective of the project was to assess suitability and awareness of building energy analysis tools for predicting energy consumption, heat transfer, ventilation flow rates, cavity air and surface temperatures and solar protection effect and interaction with building services systems for buildings with Double Skin Facades (DSF). From the literature review (Poirazis H., 2006), it was clear that an identification of a double skin facade with a typical performance is not easy, as every double skin facade building is almost unique. A set of comparative test cases was defined, simulated and analysed in the period of construction of the experimental test facility in order to help pointing out:

- areas of modelling difficulties,
- necessary empirical test cases for completing the subtask assignment, and
- important parameters to measure during the empirical test cases.

Moreover useful feedback was obtained from the participants with comments on the test case specification, measurements and the review of the comparative/experimental results. Finally, the close collaboration made the authors familiar with the tools and approaches used in the software tools participating in the subtask exercises.
There were two different test cases defined in the empirical test case specification, based on the investigated mode:

- transparent insulation mode, in which all of the openings of the DSF were closed, so there was no exchange of the zone air with the external or internal environment. The zone air temperature resulted from the conduction, convection and radiation heat exchange. The movement of the air in the DSF appeared due to convective flows in the DSF.
- external air curtain mode, in which top and bottom openings of the DSF were open to the outside, thus there was the mass exchange of the air between the cavity and outdoors caused by the natural driving forces.

The experiments were conducted in the full-scale outdoor test facility 'the Cube', located at the main campus of Aalborg University, Denmark and shown in Figure 4. The test facility consists of

Project Outcomes

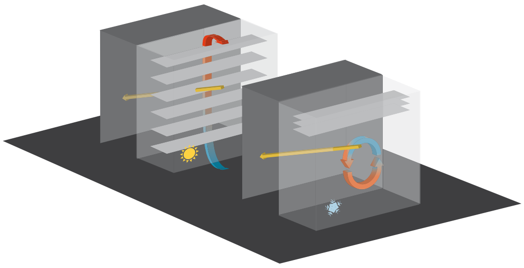


Figure 5 'The Cube' - the outdoor test facility at Aalborg University.

two main thermal zones where the measurements were carried out: the double-skin façade cavity and the experiment room, being adjacent to the DSF cavity. Results of the empirical exercises were compared between several building energy simulation programs and experiments.

The project outcome was, while night-time modeling results were in good agreement with experimental results, but in the periods of higher solar intensity, more detailed calculations or models should be applied, as the presence of solar radiation is an essential element for the double skin facade operation (only the period with the moderate solar intensity was modelled in the empirical test cases) and the models in the present validation task did not provide results of superior accuracy compared to empirical results. To achieve better performance of the models (and avoid underestimating cavity air temperatures), it is suggested to consider applying variable surface coefficients to models coefficients in order to obtain more realistic predictions during the peak loads of solar radiation.

Especially, this involves the radiation surface film coefficients and internal convective film coefficients, otherwise the air temperatures in the cavity and also the cooling power in the experimental room (zone 2) will be drastically underestimated. Additionally, none of the existing models considered recirculation flows in the DSF cavity. It is recommended to develop empirical and comparative tests cases for testing sensitivity of the following:

- wind pressure coefficients,
- discharge coefficients,
- spectral properties of glazing,
- DSF geometry in the model, and
- presence of a shading device in the DSF cavity.

This project has resulted in diagnosis of 9 modeling issues related to modeling double-skin facades, resulting in 6 improvements to 3 of the simulation programs including: BSim, TRNSYS-TUD and VA114.

Project Conclusions

The work led directly to improvements in software tools used for evaluating the impacts of energy efficiency and solar energy technologies commonly applied in innovative low-energy buildings.

Twenty four computer models were tested among the various projects. The work identified 106 results disagreements that led to 80 software or modelling fixes. Table 3 indicates the number of model errors that were identified and fixed. This indicates the utility of both empirical validation and analytical verification and comparative testing to identify disagreements that lead to corrections.

Table 2 Model fixes.

Project	Disagreement		Model tested
	Fixed	Identified	
Ground Coulpled Slab-on-Grade	19	24	9
Multi-Zone Non-Airflow	32	48	9
Airflow	1	1	6
Shading/Daylighting/Load Interaction	14	14	7
Mechanical Equipment and Controls	8	10	5
Double-Skin Fasade	6	9	5
Total	**80**	**106**	**24**

Six IEA Technical Reports were produced containing four empirical validation test suites, four comparative test suites, and several analytical verification test cases as part of the comparative test suites. In addition a comprehensive literature review on Double Façade buildings was also published as an IEA Technical Report.

Continued support of model development and validation activities is essential because occupied buildings are not amenable to classical controlled, repeatable experiments. The few buildings that are truly useful for empirical validation studies have been designed primarily as test facilities. The energy, comfort, and lighting performance of buildings depend on the interactions among a large number of transfer mechanisms, components, and systems. Simulation is the only practical way to bring a systems integration problem of this magnitude within the grasp of designers.

There is a growing body of literature and activity demonstrating the importance of the use of simulation tools for greatly reducing the energy intensity of buildings through better design. As building energy simulation programs are more widely used – such as, in the U.S. for establishing LEED ratings and federal tax deductions, in Europe to comply with the European Performance Directive, in Australia to comply with greenhouse gas emission ratings, etc. – the design and engineering communities must continue to have confidence in the quality of these programs. Such confidence and quality is best established and maintained by combining a rigorous development and validation effort with user-friendly interfaces.

Project Outcomes

Further Information

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Lemort V. Rodriguez A. Lebrun J., Simulation of HVAC Components with the help of an Equation Solver, Technical University of Liege in conjunction with IEA: SHC Task 34/ECBCS Annex 43, March 2008

Project Reports

www.iea-ebc.org

Project Participants

Category	Organisation
Australia	CSIRO
Belgium	University of Liège
Canada	Natural Resources Canada
Denmark	Aalborg University
France	University of Reunion Island Ecole des mines, Paris JNLOG CSTB
Germany	Dresden University of Technology Fraunhofer Institute for Building Physics
Ireland	Dublin Institute of Technology
Japan	Institute of National Colleges of Technology Ashikaga Institue of Technology National Institute of Environment Studies
The Netherlands	VABI Software
Norway	Norwegian Building Research Institute (NBRI) Telemark University College
Sweden	Lund University
Switzerland	EMPA Hochschule Technik & Architectur Luzern
United Kingdom	Cardiff University University of Strathclyde
USA	National Renewable Energy Laboratory J. Neymark and Associates Iowa Energy Center Iowa State University GARD Analytics Thermal Energy Systems Specialists

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