COMPUTATIONAL SUPPORT FOR THE SELECTION OF ENERGY SAVING BUILDING COMPONENTS

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ABSTRACT
This paper summarizes a PhD.-project that is currently under completion at Delft University of Technology, Faculty of Architecture, Building Physics Group. The general problem addressed in this project is the integration of building simulation tools and building design. This problem has been narrowed down to one specific type of building design decision: the selection and integration of one or more energy saving building components like solar walls, advanced glazing systems, sunspaces and photovoltaic arrays into a given building design.

The paper provides an overview of the main research efforts that were carried out during the research (de Wilde, 2003). Based on results and on views that have been described in earlier publications (e.g. van der Voorden et al., 2001) the paper then will identify relevant, challenging issues for future research in the area of integration of building simulation tools into the building design process. Specific attention will be paid to issues related to the use of different categories of tools (simulation tools as well as other instruments) for the development of new, energy-efficient building design concepts.

KEYWORDS
building design process, building simulation,
selection of energy saving building components,
strategy, prototype, future research

1. INTRODUCTION
Energy use is one of today's major problems. The human race faces the exhaustibility of the fossil fuel supplies upon which it has grown to depend, while the use of those fossil fuels causes major environmental pollution (Brundland *et al.*, 1987; UNEP, 2002). The built environment is a key factor in this issue: buildings are omnipresent and most of them use energy for heating, cooling and lighting. In the countries of the Organization for Economic Co-operation and Development the building sector accounts for one third of the final energy demand (IEA, 2002).

In order to make buildings more energy efficient an extensive set of measures and features has been developed in the recent past that contributes to minimizing the energy need of buildings, help buildings to access renewable energy sources and to utilize fossil fuels as efficiently as possible. Most of these measures and features materialize in the form of distinct, tangible ‘energy saving building components’. Examples of such components are heat pumps, sunspaces, advanced glazing systems, thermal insulation layers, etc. See figure 1.

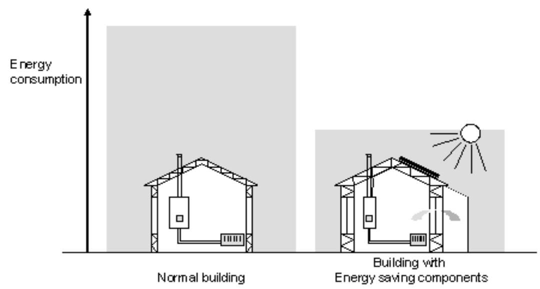

Figure 1: Energy saving building components

Design decisions regarding the selection and subsequent integration of energy saving building components need careful consideration during the building design process: the objective of making buildings energy efficient must be balanced with other, often contradicting performance objectives (e.g. thermal comfort, indoor air quality); at the same time, the possible interaction between energy saving components and a building, the impact of a large number of building design parameters (of both components and building) on the thermal behavior of the building and issues like occupant behavior, climate regime etc. add to the overall complexity of the decision.

Building simulation tools appear to be an optimal instrument to support decisions regarding the selection and integration of energy saving building components: they can provide detailed information on the performance of buildings that have not yet been built, thereby allowing objective comparison of different design options under identical conditions. However, actual use of computational tools to provide information to support building design decisions (like for instance the selection of energy saving building components) does not live up to this expectation (e.g. Crawley and Lawrie, 1997; Hand, 1998; Augenbroe, 2001; Clarke, 2001).

Therefore, the central goal of the PhD-project is the *development of a strategy to provide computational support during the building design process for rational design decisions regarding the selection of energy saving building components*. This strategy is to be substantiated by development of a prototype (which can be a new type of tool or tool environment) that demonstrates the feasibility of the strategy (de Wilde *et al.*, 1998).

A literature survey (de Wilde, 1998) of previous efforts in the field of integration of building design and building simulation shows that new, innovative technologies are employed in buildings on which no (or only little) experience is available. It also points out that buildings have to meet increasingly stringent quality demands, which are more and more formulated as quantifiable performance requirements (for instance in performance-based building codes). In order to guarantee that buildings indeed meet these demands, an increased use of computational tools is required to enable performance-based building design decision-making.

Regarding earlier efforts to integrate building simulation into and building design a large number of tool-related integration efforts has been identified; the tools resulting from these efforts can be divided in tools for designers (to be used by building designers only) and tools for design teams with experts (tools that are assuming use by simulation experts). Also a small number of tool-independent integration efforts has been identified, focusing on having the simulation expert be part of the design team.

The earlier integration efforts have identified a number of plausible barriers to the integration of building simulation in building design:

- unavailability of appropriate computational tools or models;
- lack of trust in computational results, possibly in connection with lack of usefulness and clarity of these results in a design context;
- high level of expertise needed to fully utilize building simulation tools;
- costs (time and money) connected with building simulation efforts;
- problems related to data exchange between 'design' and 'simulation'.

The review observes that development of new building energy simulation tools shows a continuous increase of capabilities and complexity. This trend seems to increase the barriers to integration of building design and building simulation even further.

Efforts on integration continue. The following approaches capture the most important ongoing attempts:

- automated data transfer, which aims at the development of a shared building model (product model) which can be accessed by different design, modeling and analysis tools, resulting in interoperability of these tools.
- consultant taking care of integration, an approach that brings the simulation experts and their tools into the design team and has these experts ensure that sufficient interaction between designers and simulationist takes place;
- re-development of simulation tools to circumvent the problem, where interoperability is re-defined from a functional and behavioral viewpoint;
- minimalistic data-transfer through process-context sensitive, light-weight interfaces.
- For a graphical depiction of these four integration approaches, see figure 2.

However, these state-of-the-art approaches towards integration are all based on a technology-push approach; none of them seems to address the whole set of barriers to integration of building design and building simulation as identified from earlier efforts.

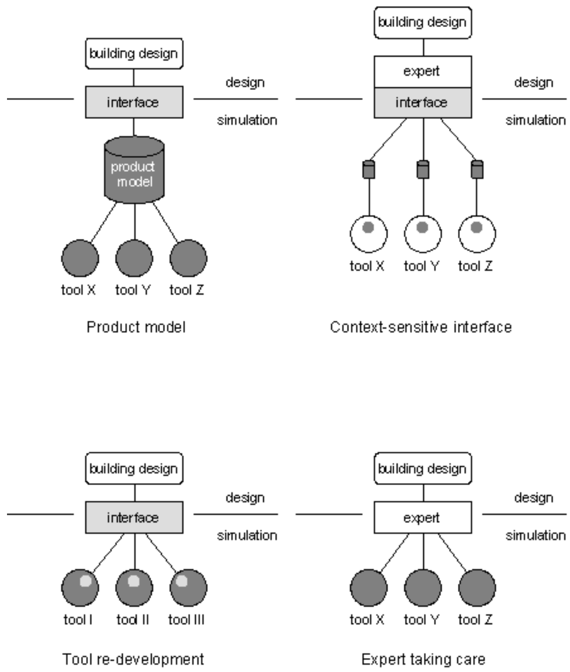

Figure 2: schematic idea of integration approaches

The literature survey concludes that many of the earlier integration efforts are biased by their up-front commitment to the development of a specific tool, limiting their contribution to the whole field. In a related issue, the earlier efforts also lack a hard analysis of the role of existing tools in current practice. It is also concluded that there are no unbiased studies available that describe how the selection of energy saving building components takes place in current building projects, and how building simulation tools are used to support this selection. Neither is there any quantitative information on the uptake of building simulation tools in current design practice.

2. ANALYSIS OF ENERGY EFFICIENT BUILDING DESIGN PROJECTS

In order to assess the current situation regarding the selection of energy saving building components and the role of computational tools in supporting this selection, a number of real, prestigious contemporary building projects in the Netherlands has been analyzed. Through case-studies the building design process of three recently completed building projects have been analyzed, providing in-depth information on the selection of energy saving building components and on the role of computational tools in the design processes of these projects. The case-studies were followed by a survey, in order to verify the validity of the results of the cases for a larger sample (de Wilde *et al.*, 1999a, de Wilde *et al.*, 1999b, de Wilde *et al.*, 2001a)

For the case-studies the design processes of the following office buildings in the Netherlands have been analyzed: Rijnland Office (Leiden), ECN Building 42 (Petten) and Dynamic Office (Haarlem; see figure 3).

Figure 3: Photo of the Dynamic Office (courtesy of Uytenhaak Architects, Amsterdam, the Netherlands)

Each case has been analyzed using an approach consisting of:

1. data gathering (collection of information through literature review and by means of dedicated interviews with the architect and consultant involved in the design project);
2. process modeling (analyzing the data gathered in step 1 and representing this information by means of IDEF-0 process models (Knowledge Based Systems Inc., 2002); to convey the idea of these diagrams see figure 4 (this is only one part of an IDEF-0 process model, at low magnification)
3. feedback interaction (reviewing the process models with the interviewees).

The results of the case-studies indicate that:

- Selection of most energy saving building components takes place during conceptual design.
- Selection of energy saving building components takes place based on use of these components by architects or consultants in earlier projects, or based on the use of these components in reference projects.
- There is virtually no selection of energy saving building components based on an equivalent comparison of the performance of several design variants.
- Building simulation tools are used after the phase of conceptual design has been finished.
- Building simulation tools are used to verify expectations about energy use or to optimize selected components; these tools are not used to support selection energy saving building components from a range of options.

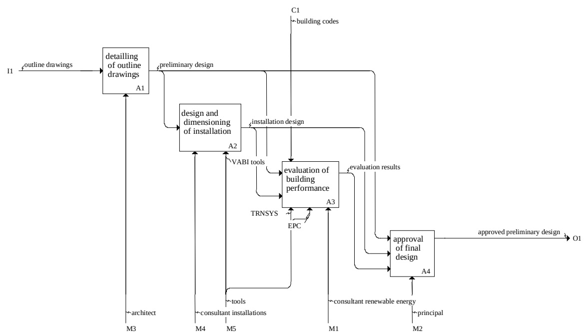

Figure 4: part of the process model describing the design process of ECN Building 42

The survey was carried out amongst the architects and consultants who had recently been involved in the design of energy-efficient buildings in the Netherlands. A set of 70 building projects (the maximum on which sufficient information was available) was selected from literature. Project-specific questionnaires were developed, with different versions for architects and consultant (each being addressing for their specific role in the project).

The response provided partial data sets (response from either architect or consultant) for 42 projects, and full data sets for 10 projects.

The results of the survey (while bearing in mind that the sample size remains quite limited) confirm the validity of the results of the case-studies:

- Most energy saving building components are selected without computational underpinning; instead, their selection seems mainly based on earlier use and analogy.

- Approximately 80% of all energy saving building components are selected without considering alternatives, which demonstrates that the decision to select a specific component is highly intuitive.

The analysis of energy-efficient building projects demonstrates the need to address both the building design process and computational tools at the same time. As long as selection of energy saving building components takes place in an intuitive manner computational results will have little impact on their selection; on the other hand, unavailability of meaningful computational results at the crucial design decision moment forces the decision-maker to base his choice on intuition.

3. ELEMENTS TO IMPROVE THE SELECTION OF ENERGY SAVING BUILDING COMPONENTS

In order to improve the current way of selecting energy saving building components a strategy has been developed to provide computational support for rational design decision-making on this aspect during building design. The strategy addresses both the building design process (the procedure for selection of energy saving building components) and the tools that must support this process (specifically the building performance assessment tools). The ingredients that have been developed as a basis for this strategy will now be presented.

For the procedural part of improving the selection of energy saving building components the building design process has been re-structured, using an applicable body of knowledge from the field of engineering design, especially systems engineering (e.g. Blanchard and Fabrycky, 1998), decision theory (e.g. Keeny and Raiffa, 1993; French, 1993) and design methodology (e.g. Cross, 1994; Roozenburg and Eekels, 1991). Based on these ingredients a procedure for the selection of energy saving building components has been developed that consists of five main steps (de Wilde *et al.*, 2001b):

1. Definition of an option space, that identifies which combinations of a given building design with one or more energy saving building components are to be considered. It is noted that in current design projects this option space was found to be almost empty; formal definition of an option space will help the design team to broaden its search.
2. Identification of the relevant functions of all design options, in order to find the relevant criteria for the selection. This should guide the team towards rational, multiple-attribute decisions, thereby taking into consideration that these components not only affect energy efficiency but other performance aspects as well.
3. Specification of performance indicators (PI), objectives, requirements and constraints. PIs allow to quantify how well a building design option performs a function. Each PI has a range; in this range, objectives represent goals, requirements represent values that must be realized. PIs that come with requirements are named constraints.
4. Prediction of the performance of all design options, for all PIs, through execution of (virtual) experiments. Mostly computational tools are used to predict performance; however, also measurements/monitoring of real buildings or experimental set-ups can be used.
5. Evaluation of predicted performance, in which a subjective assessment is made of how well each design option performs each individual function, and where a tradeoff between the performance of different functions can be made as well (for instance by applying an additive utility function).

The steps can be executed in the order as described; however, in real design practice some iteration and concurrency must be accommodated. For a general roadmap of the procedure, see figure 5.

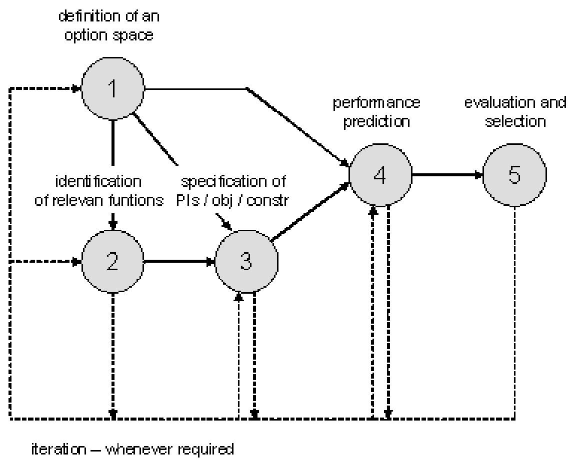

Figure 5: iteration of the steps of the approach

For the part of the improving the selection of energy saving building components that deals with support instruments, an analysis has been made of the information that is needed to support the selection of energy saving components according to the procedure. Also, the different types of support instruments that are available, and their capabilities to provide this information have been analyzed.

Within the approach for selection of energy saving building components, five different categories of information are needed:

- information that describes the (highly variable!) building design that lies at the basis of the selection work;
- information on available energy saving components, and the functions that are associated with those components;
- information on available performance indicators that can be used to quantify fulfillment of the functions;
- *performance information;*
- and information on preferences (weighting factors) that are needed for tradeoff decisions.

Support instruments for dealing with building design information are available in the architectural profession. CAD-systems, project websites, product catalogues etc all help to capture the geometry, material properties and other relevant data on (developing) designs.

Support instruments regarding energy saving building components and their functions are available in the form of handbooks, overviews etc. However, none of these currently appears to provide a complete, in-depth overview. Yet since this information is static, it will be easy to develop a database that contains this information.

Information on performance indicators is mainly available in the form of knowledge of experts in the field of building performance assessment. Support instruments in this field are mainly teaching tools and technical reports, allowing new experts to access existing performance metrics. A good overview that presents all available performance indices would be a powerful tool; however, since this again concerns static information, this again can be realized through a simple database-structure.

Support instruments that allow dealing with preferences are available in the form of decision rules and communication systems.

Performance information is the kind of data that is generated using building simulation tools. There are many simulation tools available; however, if these are to be used in a design context they must meet the following requirements

1. Tools must accommodate specific, design-driven option spaces.
2. Tools must be able to carry out the specific ‘virtual experiments’ that are relevant for the design decision in question.
3. Tools must provide relevant performance information without halting the building design process.
4. Tools that are to be used to support the selection of energy saving building components must be applicable during early design stages (feasibility study, conceptual design).

From descriptions of the functionalities of a representative set of tools it has been concluded that building simulation tools like e.g. Capsol, EnergyPlus, ESP-r, IDA-ICE and TRNSYS all meet these requirements, and all mentioned tools are capable of supporting the selection of energy saving building components, on condition that enough time is available for the required specific modeling and simulation efforts.

A number of potential developments have been identified that will help to increase the applicability of building simulation tools to support the selection of energy saving building components:

- existing tools should be analyzed in order make very clear which building design alternatives and performance indicators they can handle, which helps to speed-up the search for a suitable tool;
- further coupling of tools that assess different but related performance aspects (e.g. thermal and airflow tools), including on/off control over the coupling, is needed;
- modules that provide the user with information on accuracy of computational results can be added, in the end allowing accuracy management;
- efforts to improve existing tools on some practical, model-related issues like dealing with more complex geometry, general data formats and idealized HVAC-systems would be beneficial.

Furthermore, the development of ‘support environments’ (in which building simulation tools as well as other design support instruments can be embedded) is expected to enhance applicability of simulation tools, providing better access to (modular?) tools and models, adding the functionalities product models, common databases, process modeling and management tools, etc., adding functionalities that support the generation of new design alternatives, allowing ‘evolving’ models that follow the development of the building design, etc.

4. DEVELOPMENT OF A STRATEGY FOR THE SELECTION OF ENERGY SAVING BUILDING COMPONENTS

The above-mentioned procedural and tool-related elements have been combined into a strategy to provide computational support during the building design process for rational design decisions regarding the selection of energy saving building components that is the goal of the research project.

The essential elements of the strategy are the following:

- application of one common support environment that provides access to a process modeling facility that helps to enact the approach for performance based selection of energy saving components as described above, and all relevant tools (both simulation tools and other support instruments) that are needed within that process (approach);

- identification of PIs that are relevant for the selection of energy saving building components, and providing links to virtual experiments that are needed to obtain corresponding PI-values;
- embedding of computational tools in the common support environment that can carry out the virtual experiments and return the relevant PI values; where possible, automation of the execution from the virtual experiment from the point where a PI (and thereby the corresponding experiment) is selected;
- addition of all possible other support instruments (databases, product models, decision-making tools etc.) to the support environment that help to carry out the specific steps of the process.

In order to demonstrate the feasibility of the strategy a prototype has been developed; this development took place in the context of an international research project named the Design Analysis Interface (DAI)-Initiative (Augenbroe et al., 2003). The DAI-Initiative was a carried out by Georgia Institute of Technology, Carnegie Mellon University, and University of Pennsylvania, Philadelphia, USA. The first author particapted in this project on behalf of Delft University of Technology, and contributed to all elements.

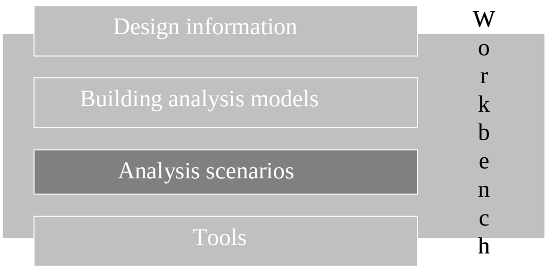

Figure 6: schema of the DAI-Workbench

The main objective of the DAI-Initiative was to develop a first-generation ‘workbench’ for design analysis interaction that can be configured and managed to respond to specific analysis requests with appropriate user defined analysis scenarios. This workbench consists of four layers that contain repositories and applications that allow to perform all the necessary steps to do an analysis of the performance of building design: a layer that holds relevant design information (both structured and un-structured), a layer containing relevant building analysis models that can be populated from the design information layer, a layer defining the task and process logic involved, and a layer that contains the performance analysis tools that can be called to actually perform building analysis. See figure 6.

In the DAI-prototype a process model drives the design-analysis interaction on the scenario layer; to convey the flavor, part of a process is depicted in figure 7. Somewhere in the process analysis tasks are encountered. In order to carry out these tasks, pre-defined analysis models (situated on the model layer) linked to tools (on the tool layer) are called, and these models will be populated with data from the design information layer. For details of the DAI-prototype the reader is referred to dedicated publications on the issue (e.g. Augenbroe et al., 2003).

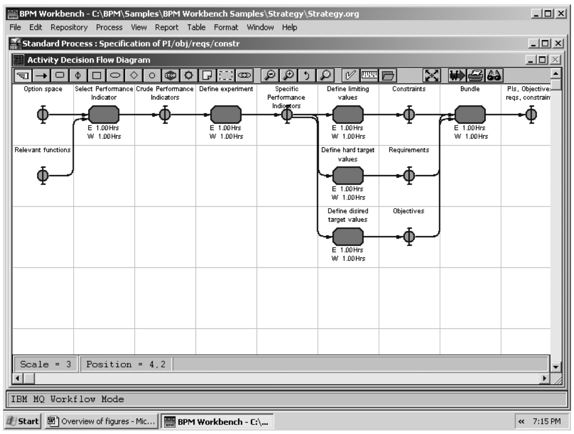

Figure 7: a process model in the scenario layer of the DAI-workbench

Regarding the selection of energy saving building components the DAI-prototype supports the adherence to the steps of the approach decribed in section 3 of this paper. It contains analysis models that quantify energy efficiency, thermal comfort and daylight autonomy, and which are linked to the simulation tools EnergyPlus and IDEA-L, demonstrating developments in the field of simulation tools and environments as described in section 3.

Thereby the DAI-prototype shows how the elements of the strategy for the selection of energy saving building components can be harnessed into a support environment; however, it must be noted that the DAI-prototype is just a proof-of-concept environment which will need substantial additional efforts to become applicable in actual design projects.

Note that support environments like the DAI-prototype are intended to support the efforts of design teams, and thereby focus on the more complex buildings (e.g. offices, public buildings). Use of such support systems in simple housing design is less likely.

The strategy and prototype described in this section contribute to integration of building simualtion and buildign design process.

By starting from design questions, and linking those design questions to explicit building performance assessments, they allow a design-oriented access to appropriate simulation models and tools.
By maximizing the automation of the steps from design question to performance assessment, problems related to data exchange, time and money are minimized. Human experts remain an essential element in both the strategy and the prototype, but human activities are supported whenever possible.
The development of a strategy and prototype do not yet solve the problem of a possible lack of trust in computational results; however, an increased transparency in analysis working procedures provides a step in this direction.

5. CONCLUSIONS

In current design projects energy saving building components are selected using analogy, intuition and simple (heuristics based) decision rules. However, the different building performance aspects (energy efficiency, thermal comfort, daylighting, …) that are influenced by energy saving building components and the complex interactions and mechanisms that interconnect these aspects make the use of multi-criteria decision rules preferable. In current projects, computational tools do not play a role impact the selection of energy saving building components, since these tools are used in later phases than those relevant for the selection, and are only used for different purposes (optimization and verification rather than to support choices).

The process of selecting energy saving building components can be improved by applying existing knowledge from engineering design. An approach for this selection, which consists of five main steps (definition of an option space, identification of functions, specification of PIs, performance prediction, and evaluation and selection) has been developed.

Existing building simulation tools have been found to be able to support performance-based selection of energy saving components, but their applicability is limited by the need for user intervention (physical modeling, input generation, post-processing of results). Work on reverse engineering of tools, coupling with on/off control, accuracy control, as well as the embedding of existing tools in dedicated support environments can help improve the applicability

In order to provide computational support during the building design process for rational design decisions regarding the selection of energy saving building components a strategy has been developed. The viability of this strategy has been demonstrated through the development of a proof-of-concept prototype of a support environment in the DAI-Initiative.

The strategy for selection of energy saving building components, and the DAI-prototype, contribute to integration of building design and building simulation.

6. ISSUES FOR FURTHER RESEARCH ON INTEGRATION OF BUILDING SIMULATION AND BUILDING DESIGN

The following issues have been identified as being relevant for further research:

- Analysis of the impact of social issues (social interaction, group behavior, politics) on design decision making regarding selection of energy saving building components; investigation of further information which might be obtained from real-time observation rather that retrospective analysis of design processes; and analysis of possible relations between building process and performance of the resulting building designs.
- In-depth analysis of the desired information that design teams would want to have about buildings with energy saving building components, rather than only a theory-based hypothesis on what design teams should consider when selecting one of these components.
- Further reverse engineering of the many building simulation tools in order to identify options spaces and performance aspects covered by these tools, which then can be compared to the needs from a design-perspective point of view.
- Analysis of the impact of the combination of uncertainties in building design (due to partial, incomplete designs etc.) with the uncertainties in building performance assessment (due to modeling, computational procedures etc.)
- Investigation of the possibilities to develop 'evolving' building models that match the development of a building design.
- Exploration of the options to use computational tools as tools to generate building design variants (use as design tools), rather than analyze performance only (use as analysis tools).

7. FINAL REMARKS

The main goal of the research presented in this paper, the development of a strategy to provide computational support during the building design process for rational design decisions regarding the selection of energy saving building components, has been achieved. The elements of the strategy have been described; a prototype support environment shows how the strategy can be harnessed in a support environment that supports interaction between building design and building simulation. The novel element here, setting the prototype apart from e.g. the IAI-BLISS work by LBNL (2003) is the introduction of a scoping mechanism that links building design and building analysis. However, it must be noted that introduction of fully functional support environments in building design practice still requires a lot of research and development efforts.

REFERENCES

Augenbroe, G., 2001. Building simulation trends going into the new millenium. Keynote. *Building Simulation '01, 7th International IBPSA Conference*, Rio de Janeiro, Brazil, august 13-15 2001, 15-27

Augenbroe, G. et al., 2003. The Design Analysis Interface Initiative. Paper submitted for *Building Simulation 2003*, Eindhoven, the Netherlands (these proceedings)

Blanchard, B.S., Fabrycky, W.J., 1998. *Systems engineering and analysis.* 3rd ed. Upper Saddle River: Prentice Hall

Brundtland, G.H. et al., 1987. *Our common future.* Oxford: Oxford University Press

Clarke, J.A., 2001. *Energy Simulation in Building Design.* 2nd ed. Oxford: Butterworth-Heinemann

Crawley, D.B., Lawrie, L.K., 1997. What next for building energy simulation – a glimpse of the future. *Building Simulation '97, 5th International IBPSA Conference*, Prague, Czech Republic, September 8-10 1997, volume II, 395-402

Cross, N., 1994. *Engineering design methods*. 2nd ed. , Chichester: John Wiley & Sons

French, S., 1993. *Decision theory - an introduction to the mathematics of rationality*. 2nd ed. Chichester: Ellis Horwood Limited

Hand, J.W., 1998. *Removing barriers to the use of simulation in the building design professions*. Thesis (PhD). University of Srathclyde, Department of Mechanical Engineering, Energy Systems Research Unit, Glasgow, UK

International Energy Agency. (2002). *Key world energy statistics* [online]. Available from: http://www.iea.org/statist/index.htm.

Keeney, R.L., Raiffa, H., 1993. *Decisions with multiple objectives - preferences and value tradeoffs.* Cambridge: Cambridge University Press

Lawrence Berkeley National Laboratory. (2003). Building Life-Cycle Information Support System [online]. Available from http://eetd.lbl.gov/btp/cbs/BPA/bliss.html.

Roozenburg, N., Eekels, J., 1991. *Productontwerpen, structuur en methoden.* Utrecht: Lemma

United Nations Environment Programme. (2002a). *UNEP – Homepage* [online]. United Nations Environment Programme, Geneva, Switzerland. Available from: http://www.unep.org [Accessed 27 May 2002]

van der Voorden, M., P. de Wilde, G. Augenbroe, 2001. Beter ontwerp door gebouwprestatie-simulatie? Proceedings of the Third IBPSA-NVL Conference, Petten, the Netherlands, December 2001 (in Dutch)

de Wilde, P., 1998. *Integratie van ontwikkelde energiebesparende componenten in bestaande gebouwconcepten.* Internal report ECN-I-98-011, Netherlands Energy Research Foundation ECN

de Wilde, P., M. van der Voorden, G. Augenbroe, 1998. Towards a strategy for the use of simulation tools as support instrument in building design. *System Simulation in Buildings 1998, Fifth International Conference*, Liège, Belgium, December 14-16 1998, paper 28 (CD-ROM)

de Wilde, P., G. Augenbroe, M. van der Voorden, 1999(a). Effective use of building simulation tools as support instrument in building design. *North Sun 1999, 8th International Conference on Solar Energy in High Latitudes*, Edmonton, Canada, August 12-14 (CD-ROM)

de Wilde, P., G. Augenbroe, M. van der Voorden, 1999(b). Invocation of building simulation tools in building design practice. *Building Simulation '99, 6th International IBPSA Conference*, Kyoto, Japan., September 13-15 1999, 1211-1218

de Wilde, P., M. van der Voorden, J. Brouwer, G. Augenbroe, H. Kaan, 2001(a). Assessment of the need for computational support in energy-efficient design projects in the Netherlands. *Building Simulation '01, 7th International IBPSA Conference*, Rio de Janeiro, Brazil, august 13-15 2001, 513-520.

de Wilde, P., M. van der Voorden, G. Augenbroe, 2001(b). A strategy to provide computational support for the selection of energy saving components. *Building Simulation '01, 7th International IBPSA Conference, Rio de Janeiro, Brazil, august 13-15 2001, 653-660*

de Wilde. P., 2003. *Computational Support for the Selection of Energy Saving Building Components*. PhD-thesis (in preparation). Delft University of Technology, Faculty of Architecture, Building Physics Group, Delft, the Netherlands

Knowledge Based Systems Inc. (2002). *IDEF-0 Overview* [online]. Available from http://www.idef.com/overviews/idef0.htm