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## **Towards More Effective Use of Building Performance Simulation in Design**

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Abstract: This paper discusses some issues which hinder effective use of building performance simulation in building design, and some approaches towards better and more efficient use of this important but underutilized technology. In particular, the paper discusses the issues of quality assurance, the relative slow software developments and the limited use (usability) of building performance simulation mainly during the final stages of the building design process.

### **1. INTRODUCTION**

Computer modeling and simulation is a powerful technology for addressing interacting architectural, mechanical, and civil engineering issues in buildings. Building performance simulation can help in reducing emission of greenhouse gasses and in providing substantial improvements in fuel consumption and comfort levels, by treating buildings and the systems which service them as complete optimized entities and not as the sum of a number of separately designed and optimized sub-systems or components. It is only by taking into account dynamic interactions, as indicated in Figure 1, that a complete understanding of building behavior can be obtained.

For more than a quarter of a century, building performance simulation programs have been developed to undertake non-trivial building (design) analysis and appraisals (Kusuda 2001). The techniques of building performance simulation are undergoing rapid change. Dramatic

improvements in computing power, algorithms, and physical data make it possible to simulate physical processes at levels of detail and time scales that were not feasible only a few years ago. Although contemporary programs are able to deliver an impressive array of performance assessments (see e.g. Augenbroe and Hensen 2004, Hensen and Nakahara 2001, Hong et al. 2000), there are many barriers to their routine application in practice, mainly, in the areas of quality assurance, task sharing in program development and program interoperability (see e.g. Augenbroe and Eastman 1998, Bazjanac and Crawley 1999, Blis 2002, Bloor and Owen 1995, Crawley and Lawrie 1997, Eastman 1999), and because the use is mainly restricted to the final stages of the overall building design process.

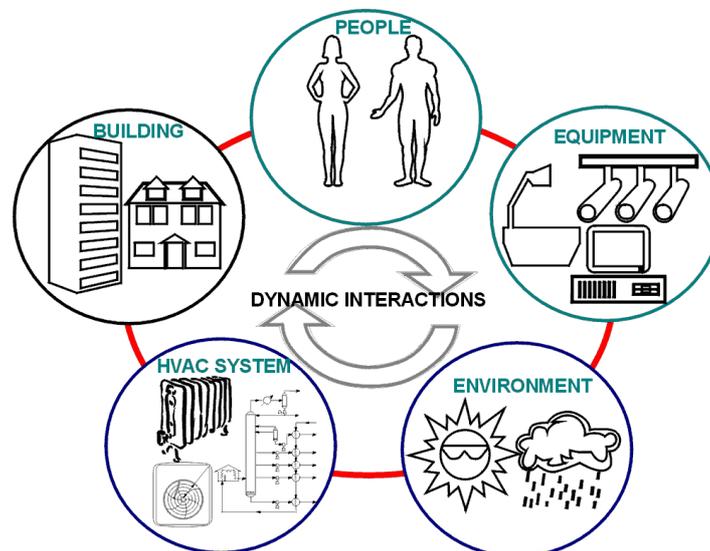


Figure 1. Dynamic interacting sub-systems in a building context

This paper describes ongoing work which aims to address some of these issues. The work is carried out within the research group "Building Simulation for Integrated Solutions" of the Center for Building & Systems TNO-TU/e. The ultimate goal is to provide tools, knowledge and procedures for integrated design and operation processes which lead to innovative, elegant and simple building designs with (a) a balanced attention to the value systems of the building occupier, building owner and the environment, (b) a better quality, (c) a shorter design time, and (d) lower life-cycle costs. The current work is an essential step towards such an innovative, integrated design and operation environment.

## 2. QUALITY ASSURANCE

Quality assurance is a very important element in any simulation task. It obviously involves the use of verified and validated software. An important international effort in this area is the ongoing international BESTEST initiative (e.g. Judkoff and Neymark 1995, Neymark et al. 2001), which is now finding its first footholds in professional standards (e.g. the proposed Standard Method of Test by the American Society of Heating, Refrigeration and Air-conditioning Engineers – ASHRAE – SMOT 140) and national standards (e.g. the Energie Diagnose Referentie – EDR effort in The Netherlands).

However there are two additional important elements which are very often underestimated when using computer simulation in the context of building design.

- Using a correct simulation methodology as well as the appropriate level of modeling resolution. For example, simulation is much more effective when used for comparing the predicted performance of design alternatives, rather than when used to predict the performance of a single design solution in absolute sense. In practice it is also often seen that high resolution modeling approaches, in particular computational fluid dynamics (CFD), and ray tracing rendering methods are used for applications where a lower resolution method would be quite sufficient and much more efficient.
- Solving the right equations sufficiently accurate, as opposed to solving the wrong equations right. Of course a user should know which parameter values should be input in the model. In addition, there are now many modeling approaches where a user should also decide which model to use. This is specifically the case in many open simulation environments (e.g. Matlab toolboxes) and in higher resolution approaches (think of wall functions and turbulence models in CFD, and the various models involved in ray tracing).

As argued before (e.g. Hensen 1991, 1993, Hensen and Clarke 2000) a first and paramount requirement for the above is sufficient domain knowledge by the user of the software. Apart from domain knowledge, it is also very important to make future engineers aware of these issues and to teach them knowledge and skills to be able to deliver quality in later design practice. Therefore it is an important topic in courses such as “Introduction -”, “State-of-art – “ and “Capita Selecta of building performance simulation”.

### **3. SHARING DEVELOPMENTS**

A frequently encountered problem by engineers who would like to simulate the future behavior of building and system design alternatives is that certain performance aspects or specific building and system components are only represented in one simulation environment while other performance aspects or components are only available in other software. Previously (e.g. in Hensen 1991, 1993, 1995, 2000) it has been argued that in the area of system simulation there is enormous amount of work to be done. When compared to the building side, one could say that every single component is like a new type of building in itself. This implies that system modeling and simulation capabilities develop very slowly and take up an enormous amount of resources (time wise and financial). Therefore, it has been suggested that sharing of developments by means of “open” simulation environments would be the best way forward.

Open simulation environments will allow components, features and models to be provided by other stakeholders (producers, re-sellers, etc who could provide models as additional product documentation) as opposed to only by software developers and researchers. Open building performance simulation environments would also make it easier to consider different performance aspects (comfort, health, productivity, energy. etc.) at different levels of resolution in terms of time and space (region, town, district, building, construction element, etc). (The building modeling and simulation laboratory metaphor.)

The four main strategies to enable sharing of distributed developments are as follows.

#### **3.1 Data and process model integration**

This is the traditional and most widely used approach, which does not lead to an actually open simulation environment. It is based on providing a facility to simulate different sub-domains within the same program. An integrated program supports information exchange throughout a simulation. Some simulation programs already integrate thermal, ventilation, air quality, electrical power and lighting calculations; e.g. ESP-r. Integration can also be achieved by merging existing applications and/or hard-wire connections such as was done in the case of TRNSYS, ISIBAT and COMIS and is currently being done in the case of EnergyPlus.

There have been – and are - many research projects in this area. Examples based on proprietary software are the Energy Kernel System (Clarke 1986a, 2001), the Intelligent, Integrated Building Design System (Clarke 1986b, 2001), the SEMPER/ S2 project (Mahdavi et al. 1999), the

Building Design Advisor project (Papamichael et al. 1997), and Ecotect. Examples that are based on a general simulation environment (Matlab / Simulink) are Simbad and Climasim.

From a user point of view, the main disadvantage of this approach is that the user is still restricted to the options / features offered by a particular environment or program, which is developed by single research unit or a small group of researchers. The latter doesn't make it very attractive for other researchers to join in a later phase. Another big problem is how to ensure the long-term maintenance of the software and associated libraries.

It is the author's opinion that this approach is only a temporary solution at best. In the long run it is deemed to fail, because it does not really enable shared developments. The environment controller / supervisor has to integrate on behalf of the users. Probably the most promising developments in this approach are those that are based on a general simulation platform such as Matlab / Simulink.

### **3.2 Data model interoperation**

In this approach, interoperability between programs is achieved on the level of the product (i.e. building and systems) model. Two approaches may be distinguished.

- Product model data sharing. Model sharing allows the domain-specific applications to extract the data required for their own purpose from a single data management system that holds both the geometrical and physical parts of the model. A typical industrial example is the VABI Uniform Environment. A research example is the COMBINE project (Augenbroe 1994). This approach avoids redundancy of data, but does not entirely prevent inconsistency and still requires an important data management system. When the model is modified, all the other parties have to be informed so that they may download it.
- Product model data exchange. Applications exchange a model, in whole or part, by using a data exchange facility generally based on a standardized neutral file format. While IGES or DXF formats only describe the geometrical part of the model, the Industry Foundation Classes (IFC) by the International Alliance for Interoperability (IAI) include both the geometrical and the physical parts. A recent development in this area is the use of eXtensible Markup Language (XML) as a means to exchange product model data over the world wide web. Product model data exchange simplifies model construction, but, as there is still one model per application, may not the problems of inconsistency (model maintenance).

Data model interoperation has moved in the realm of industry. Only a limited amount of domain specific research is needed. Most development work is related to agreeing class formats, contents, etc. Probably there is some computer science research needed.

### **3.3 Process model interoperation**

In this approach, interoperation is achieved on the level of the models that describe the thermal, flow, and other physical processes. It has long been realized that especially in the area of system simulation there is still an enormous amount of development work to be done. Therefore it has been suggested that work should be done not only towards the re-use of existing component models (i.e. interoperation at source code level by exchanging component models; for instance incorporation of TRNSYS and other component models in ESP-r (Hensen 1991)) but also in a more generic way by expressing models in a neutral format.

The Neutral Model Format (NMF) has recently merged with the Modelica project that is much wider in scope. The goal of Modelica is to design a physical systems modeling language that makes life for the model builders considerably easier and more productive.

Modeling languages often do not adequately support the structuring of large, complex models and the process of model evolution in general. Among the recent research results in modeling and simulation, two concepts have strong relevance to this problem: (1) object oriented modeling languages already demonstrated how object oriented concepts can be successfully employed to support hierarchical structuring, reuse and evolution of large and complex models independent from the application domain; and (2) non-causal modeling demonstrated that the traditional simulation abstraction - the input/output block - can be generalized by relaxing the causality constraints, i.e., by not committing ports to an 'input' or 'output' role early. This generalization enables both simpler models and more efficient simulation.

Process model interoperation has also moved in the realm of industrial research and development. Computer science research is still needed. Only a limited amount of domain specific research seems to be needed. Most development work is related to agreeing procedure, formats, etc.

### **3.4 Data model and process model co-operation**

In this approach, programs provide the facility to link applications at run-time in order to co-operatively exchange information. In early examples, one application controls the simulation and calls the other application(s) when

necessary. In this case, only the simulation engine of the coupled program(s) is required and the front-end interface corresponds to the driving application. The main advantage of the coupled approach is that it supports the exchange of information during a simulation contrary to the previous approaches. For example, Janak (1998) has enabled a one-way run-time coupling between the ray-tracing lighting and visualization application Radiance, and ESP-r.

The run-time coupling approach – as schematically shown in Figure 2 - is in the author's view currently the most promising direction for task-shared developments. We are currently carrying out three research projects in this area which focus on two-way coupling of building energy simulation with separate software packages for control simulation (Yahiaoui et al. 2004), system simulation (Radosevic and Hensen 2004) and computational fluid dynamics software (Djunaedy et al. 2004).

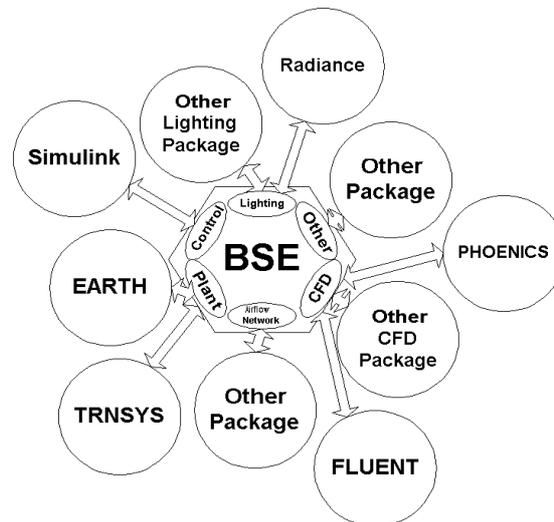


Figure 2. Schematic view of a distributed integrated building simulation environment based on an advanced multi-zone building simulation software run-time linked to external software packages

The main aim of our work is to research and implement (options for) inter-process communication. This, in turn, should enable run-time coupling of simulation softwares and thus it should become possible to run two or more simulation programs in parallel where each program represents only that part of the building and systems which it is able to model. A typical application example is shown in Figure 3.

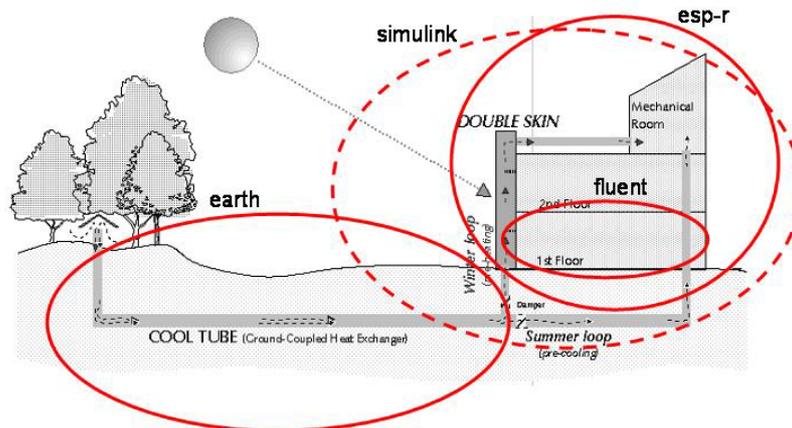


Figure 3. Schematic of an example super-low-energy building with a double-skin façade and a ground coupled heat exchanger for pre-heating or pre-cooling of fresh ventilation air. The overall configuration is simulated with run-time coupled models in Earth, Simulink, ESP-r and Fluent for the ground coupled heat-exchanger, the controls, the overall building and the air flow field in one of the thermal zones, resp.

The inter-process communication is being developed in a general sense. The results are implemented and tested in at least three different simulation environments, two of which are building domain specific (e.g. ESP-r and TRNSYS) and others are domain independent (MATLAB / Simulink and Fluent).

A key feature of the new functionality will be flexibility in terms of building systems definition from the user point of view; i.e. the user will no longer be restricted to system (and system component) options / features on offer in a particular tool, but, by combining simulation tools, will be able to model any building and system combination.

The extended design tools will be used / tested to assess and compare the performance of various innovative building and systems combinations such as, for example, earth coupled heat exchangers, combined heat and power, embedded renewable energy systems, etc. The research will include physical verification with experimental results and utilitarian verification by means of practical application in at least two realistic industry relevant design studies.

The research outcome will be a prototype system and general knowledge regarding the coupling of building and system simulation software. Although the current work concerns run-time coupling of specific simulation

environments, the coupling mechanisms and data-exchange protocols that will be developed, will ensure that the approach has general and wide applicability.

#### 4. SCOPE EXPANSION

The uptake of building performance simulation in current building design projects is limited. Although there is a large number of building simulation tools available (e.g. DOE 2003), the actual application of these tools is mostly restricted to the final building design. The main applications of building simulation in current building design projects are code compliance checking and thermal load calculations for sizing of heating and air-conditioning systems; in other words: analysis (of a single solution) rather than (multiple variant) design oriented (e.g. Altavilla et al. 2004). In an increasing number of cases this is complemented with high-resolution (light and airflow) modeling; apparently primarily to impress the client.

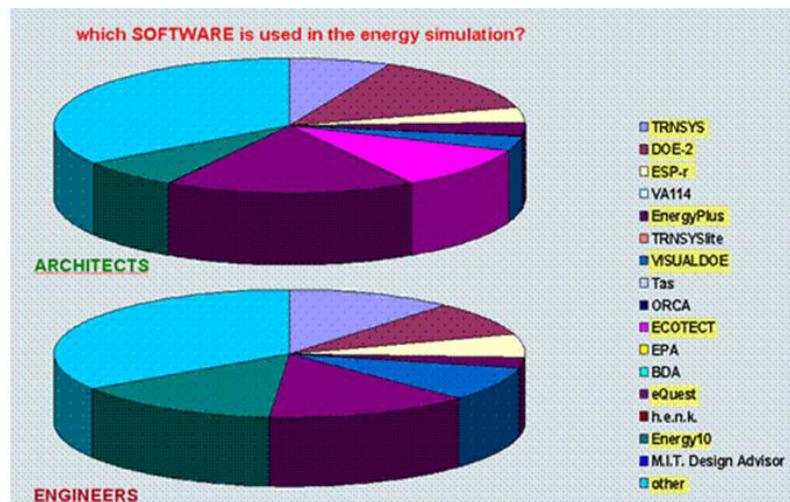


Figure 4. Results of a recent review related to software being used for building energy simulation in design (Altavilla et al. 2004)

Many tools start from the same level and are (to be) used in a similar manner. Many building performance simulation tools are not really used for

design, probably because there is a mismatch between the anticipated user and the real user in terms of expectations, background knowledge, skills, and available resources.

Many of the building performance tools that are currently in use are legacy software tools that have a monolithic software structure, and are becoming increasingly hard to maintain. Use of these tools requires expert skills to run an analysis in a way that the right output is generated from which the desired performance data can be generated.

Although it is evident that the impact of design decisions is greatest in earlier design phases, building performance simulation is rarely used at all for supporting early design phase tasks such as feasibility studies and conceptual design evaluations.

Simulation tools are not used to support the generation of design alternatives, nor to make informed choices between different design options, and they are neither used for building and / or system optimization (De Wilde, 2004).

There is an increasing awareness in design practice as well as in the building simulation research community that there is no need for more of the same. However there is definitely a need for more effective and efficient design decision support applications.

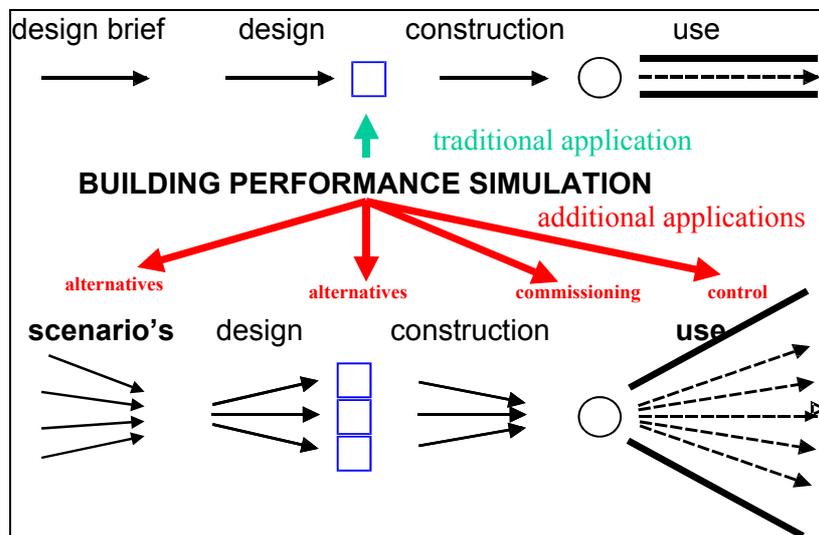


Figure 5. Expanding the scope of building performance simulation

The aim is to improve the use and usefulness of building performance simulation during the (early phase) design of a building, by researching new, innovative, next generation building performance simulation models and

applications that meet the needs of the architecture, engineering and construction (AEC) industry.

This research will focus on providing tools for ‘avant-garde’ consultants who take a pro-active role in the building design process. The specific scope will comprise the domains of building physics, heating, ventilation, air-conditioning (HVAC) and thermal storage systems. The main objectives are to research and enable innovative application of building performance simulation for design support, in particular for:

- A. generation and selection of design alternatives during early phases in the design process, where decisions have to be made with limited resources and on the basis of limited knowledge but which will have a major impact and consequences during the remainder of the building life cycle;
- B. design optimization during the early and later phases of the design process, where currently building simulation is merely used for code compliance checking.

The research will be broken up in two PhD projects, corresponding to the simulation application fields A and B above. In each case, the main questions to be addressed are:

- What are the prime analysis needs for this application of building performance simulation?
- What is the optimum model resolution level to address these analysis needs?
- How can models with this level of resolution be generated, expanded or reduced from existing models?
- What would be an appropriate performance assessment methodology for that phase given the background, objectives, needs and resources of the stakeholder(s) and practitioners in question?
- How to satisfy the simulation output requirements both in view of the designer and in view of other design team members including the client?

Both projects will have in common that they will start with a literature review, analysis of state-of-the-art building performance simulation software, and in-depth interviews or short-term observation assignments with actual stakeholders, e.g. consulting engineers and contractors. The main objective of this first phase is to bring the researcher up-to-date, to clarify the research objectives, and to specify research program. Both projects will use iterative rapid prototyping as the main research method. Subsequent prototypes will be calibrated and tested on real world problems and with actual stakeholders and practitioners. Where necessary the developed models will be validated with results from experiments under controlled conditions in a laboratory setting. The overall project will have a potential users forum

that will be consulted in general and will be involved in terms of utilitarian evaluation in particular.

The main results will include innovative, multi-purpose, multi-actor and multi-level model(s) of the building and its HVAC systems, as well as applicable building performance assessment methodologies. An important goal is that the models for the different design phases and the different applications can be generated from previous ones whenever possible, using inheritance and expansion or reduction. The results and deliverables will include the following:

- Strategic methodological knowledge and practical implementation experience regarding building performance simulation for conceptual design of building and systems.
- Strategic methodological knowledge and practical implementation experience regarding building performance simulation for optimizing the design of building and systems.
- A proto-type simulation-based design environment for early phase design and optimization of buildings and systems.
- Guidelines regarding the necessity/ applicability of building performance simulation for the early design stages.

Although the current work will involve a prototype based on a specific simulation environment, the mechanisms and protocols that will be developed will ensure that the approach has a much wider and general applicability.

#### **4.1 Building simulation for conceptual design**

The specific scope will be to support one specific role of these consultants: that of helping the design team to generate new design concepts ('design development') for the façade, the structure assisted thermal storage and the HVAC-system.

For this project the HVAC-consultant acts as the interface between design process and building performance simulation tools. This consultant will react to design questions and identifies the analysis activities that are needed (based on his experience/expertise), and then needs access to tools that help to carry out those analysis activities. The research will consist of an in-depth study of 'design development' tasks of the HVAC consultant, resulting in a requirement specification for building performance tools that support 'design development'. This specification will then be used to assess existing tools, e.g. ESP-r (ESRU 2003), VA114 (VABI 1993), h.e.n.k. (Itard 2003) and to identify the applicability of existing tools to support 'design development'. Using the rapid prototyping technique mentioned above, the

project will, depending on the outcome of the previous phase, then either develop the technology and models that enable the use of existing tools for ‘design development’, or develop new tools and models that are able to meet these requirements.

In the design of façades, structure assisted thermal storage and HVAC-systems different performance aspects play a role. The prime factors are thermal aspects: thermal comfort and energy efficiency. Other related aspects (daylighting, artificial lighting, air flow etc) will be considered whenever relevant. Furthermore, the project will need to pay attention to the development of building design information during the building design process, the use of default values and assumptions (and related consequences for the uncertainty in performance predictions) whenever design information is missing, and the possibilities to capture this information in building product models. Due to the nature of ‘design development’ the research will need to deal with the initial development /set up/ reuse and configuration of simulation models. The development of novel ‘shells’ and (graphical) user interfaces for simulation tools is expected to play an important role in this project.

Practitioners need early stage, strategic design decision support tools. In the area of indoor environment, building physics and building systems complex interactions exist which are very difficult - if not impossible - to capture and represent in rules or other forms of explicit knowledge for use in knowledge based systems. This is the main reason why many current knowledge based tools are often restricted to single issues. To be able to integrate various issues as discussed above, a combination of knowledge base and simulation could well be the solution.

In conceptual design it is important to be able to evaluate multiple concepts, and to quantify, rank-order, and even to be able to semi-automatically generate design alternatives. Qualification and quantification of variant solutions is here more important than detailed assessment of a single case. Therefore, in this approach the level of resolution can be generally low. The project will be carried out in close collaboration with PhD project B, which targets the same consultants and building systems but focuses on a different role in a later design stage.

## **4.2 Building simulation for design optimization**

This research will also focus on providing tools for ‘avant-garde’ consultants who take a pro-active role in the building design process. In this project the specific scope will be to support this consultant in optimizing the façade, structure assisted thermal storage and the HVAC-systems.

Again the HVAC-consultant acts as the interface between design process and building performance simulation tools, reacting to design questions and translating those to optimization tasks that can be carried out using building performance simulation tools. This research will consist of an in-depth study of 'design optimization' tasks of the HVAC consultant, resulting in a requirement specification for building performance tools that support 'design optimization'. This specification will then be used to assess existing tools, e.g. ESP-r (ESRU 2003), VA114 (VABI 1993), h.e.n.k. (Itard 2003) and to identify the applicability of existing tools to support 'design optimization. Using the rapid prototyping technique mentioned above, the project will then develop the technology and models that enable the use of existing tools for 'design optimization'. The project will need to closely study the relation between 'design development' and 'design optimization' and the resulting options to reuse, expand and/or reduce models that have been used for 'design development'.

Again, the prime performance aspects to be considered are thermal comfort and energy efficiency, adding other related aspects whenever relevant. The development of building design information during 'design optimization', use of default values and assumptions (uncertainty), building product models, shells and user interfaces for simulation tools will play an important role in this project as well. The project will be carried out in close collaboration with PhD project A.

## 5. IN CONCLUSION

This paper discusses some of the issues which hinder effective use of building performance simulation in building design, namely the issues of quality assurance, the relative slow software developments and the limited use (usability) of simulation during only part of the design process. Some approaches leading to better and more efficient use of this important but underutilized technology have been described.

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