Simulation for Performance Based Building and Systems Design: Some Issues and Solution Directions

Jan Hensen
Center for Building and Systems TNO-TU/e and
Eindhoven University of Technology, Netherlands

ABSTRACT

This paper is about adequate deployment of building performance simulation in decision support for integrated building and systems design. The underlying issues are sketched. The main thrust of the paper is to describe ongoing and future research in this area.

1 INTRODUCTION

For more than a quarter of a century, building performance simulation programs have been developed to undertake non-trivial building (design) analysis and appraisals. In general these programs deal only with a small sub-set of the overall problem. However, advanced architectural developments require an integrated approach to design. The domains of building physics, heating, ventilation, air-conditioning and thermal storage systems, for example, are often closely related and it is only by taking into account their dynamic interactions, as indicated in Figure 1, that a complete understanding of building behavior can be obtained. There is a need to treat buildings and the systems that service them as complete optimized entities and not as the sum of a number of separately designed and optimized sub-systems or components.

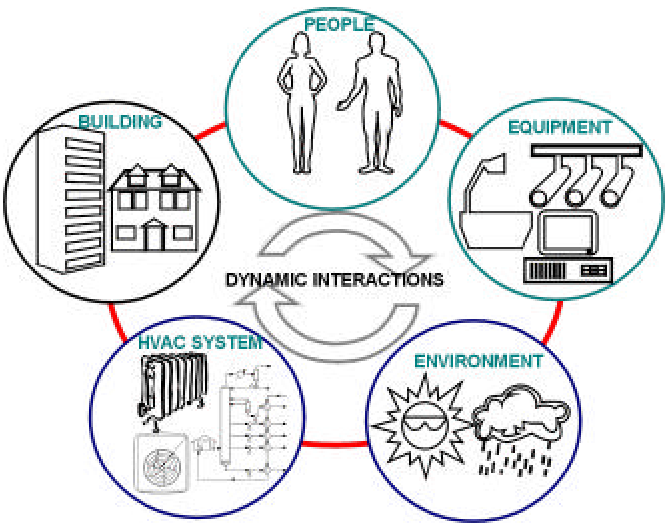

Figure 1 **Dynamic interacting sub-systems in a building context**

2 SIMULATION FOR BUILDING DESIGN

Figure 2 sketches the evolution of interest in building performance simulation for building design. We are now at the point where it is important to try to raise the realistic level by increasing the usability of this technology for performance based building and systems design.

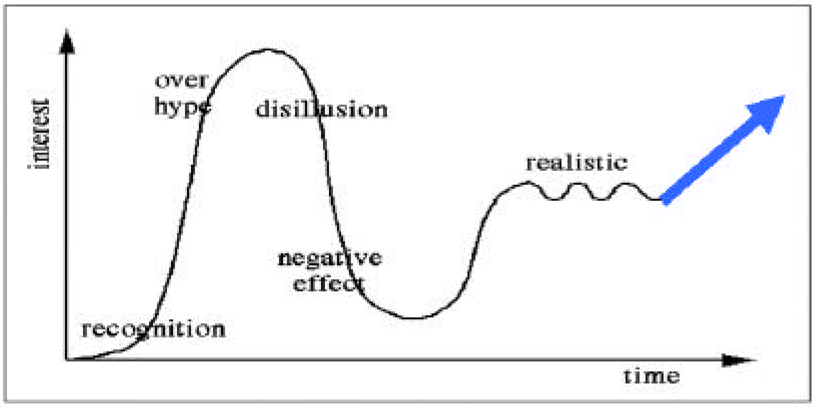

Figure 2: **Schematic evolution of interest in - and uptake of – building performance simulation since approximately 1970 until the start of the 3rd millennium**

As implied by Figure 3, in practice there are actually many more professionals who use building performance simulation than is commonly realized. However, in most cases this is still indirectly. Of course the technology could be much more effectively applied through the direct route. In 1993 it was still expected that some sort of intelligent human-computer interface would be required for this. As will be elaborated in this paper, this idea has somewhat changed since those days.

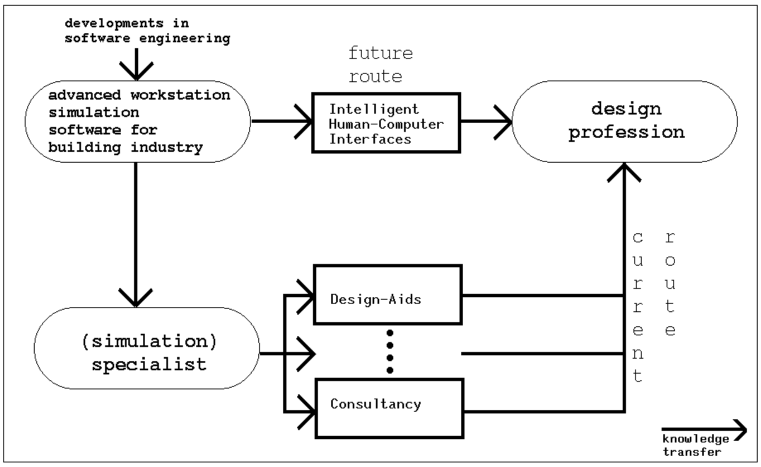

Figure 3**: Direct and indirect usage of building performance simulation (Hensen 1993)**

3 CURRENT ISSUES & CHALLENGES

It will be clear that as the technology becomes more widely applied, the demands on simulation programs will grow. The upshot of this is that increased demand will force further developments. However, it is also problematic because the underlying issues are highly complex. Although contemporary programs are able to deliver an impressive array of performance assessments, there are many barriers to their routine application in practice. The main issues, which must be addressed, include:

- Accuracy and confidence in the results.
- Technical promises are only partly achieved.
    - Simulation is mainly used for detailed design confirmation.
    - Most building and system models are limited in their capabilities.
    - System simulation is not very well developed yet.
    - Many building systems and components cannot be simulated yet.
- Simulation can be costly; especially in case of high resolution modeling

What follows are possible solution approaches including (1) quality assurance, (2) research on how to make current tools more effective in building design, (3) sharing of software developments, and (4) knowledge transfer.

4 SOLUTION APPROACHES

4.1 **Quality assurance**

In terms of quality assurance, there have been – and still are – many efforts related to validation and verification of building performance simulation software itself. A perhaps even more important aspect, which received much less attention until now, is how to assure the quality of applying the software. This is very much related to knowledge and skills of the person who performs the simulation, and to the quality of performance assessment methodologies and procedures.

It was a rather naïve idea during the seventies and eighties that it would be possible to include sufficient "intelligence" in building performance simulation software so that "anyone" would be able to carry out relevant simulations. It is now commonly accepted that this will only be possible for a limited number of very specific, relatively simple, well-defined simulation tasks such as some code compliance checks, which can, for example, be driven from a CAD package. However, even in these cases the user needs to have sufficient domain knowledge in order to be able to interpret the results in a meaningful manner.

In the real world, simulation tools are "never" able to do exactly what a designer wants, because they usually want to assess novel and innovative solutions that are

commonly not yet featured in the software.
Simulation for design decision support is not merely software; it is an engineering discipline that, in summary, is critically dependent on the following user requirements.

- Sufficient domain knowledge and understanding of fundamentals and basic principles, which, as indicated in Figure 4, increases with modeling resolution level.
- The ability to creatively solve real world problems.
- Knowledge of which software tools to use, when, why and how.

Simulation quality assurance needs to incorporate the following aspects.

- Selection of appropriate level of modeling resolution and complexity.
- Calibration of validated software.
- Proper (design) application methodology taking into account uncertainty considerations applied to the input (design) parameters.

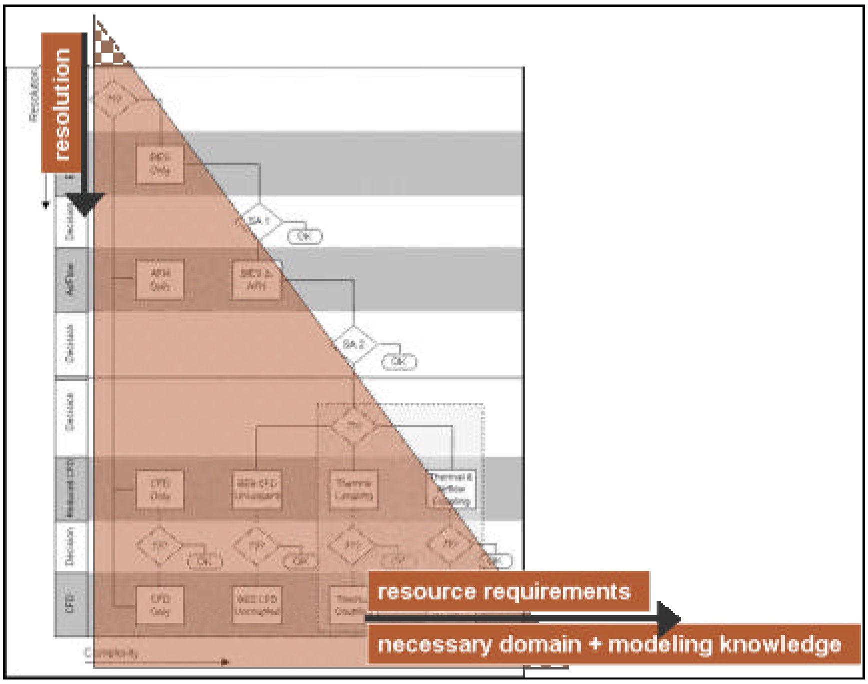

Figure 4**: Example (air flow) performance assessment methodology with indication of increasing user and resource requirements with increasing modeling resolution**

Our current research in this area involves performance assessment methodologies for specific aspects, such as air flow modeling and simulation (Djunaedy and Hensen 2002). Obviously quality assurance is an integral part of our other research projects and one of the main focus points in teaching and knowledge transfer activities; see Section 4.5.

4.2 **Better design decision support**

The main issues in building performance simulation in terms of design decision support can be summarized as follows.

- The, until now, most common approach is detailed design confirmation, which is analysis (of a single solution) rather than (multiple variant) design oriented.
- Often this involves high-resolution (light and flow) modeling just to impress the client. If it is just "colors for directors" what is requested, why are current lower-resolution tools not able to provide these sorts of results?
- Many tools are not really used in 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 tools start from the same level and are (to be) used in a similar manner. There is an increasing awareness in design practice 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.

Our current work in this area involves research that aims to find out (1) which designers would like to use simulation tools in the first place and (2) the requirements for these tools in terms of user-interface and design decision support features. We want to stress "support" so that future tools may help (not attempt to take over) the designer in his/her task at hand. Specific issues which will be considered in this research include the potential of data mining, design optimization, design analysis integration, use of component based systems templates, etc.

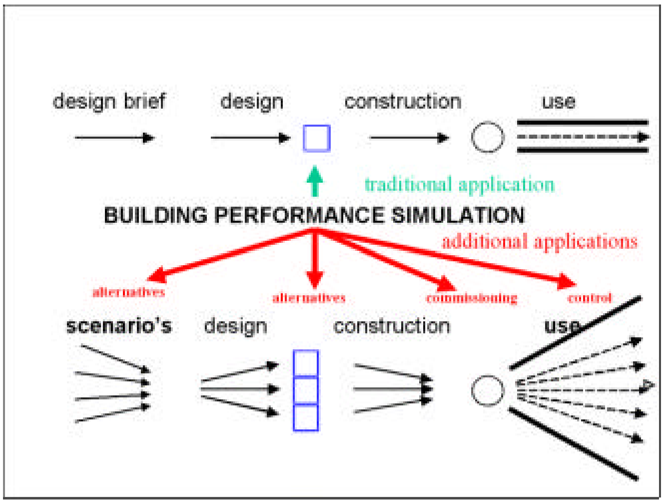

Figure 5**: Expanding the scope of building performance simulation by additional applications during the building life cycle**

4.3 **Scope expansion**

Modeling and simulation of building performance is currently mainly used for detailed design. As indicated in Figure 5, it is however possible to use modeling and simulation both in earlier and later stages of the building life cycle.

4.3.1 *Conceptual design applications*

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 main aim of our current project in this area is to research the possibilities for use of modeling and simulation during early stages in the design process.

4.3.2 Post-design applications

As indicated above, building performance simulation is currently mostly used for design. Potentially, there are however various additional applications during the subsequent lifetime of the building. Simulation can be used, for example, to aid in the commissioning of a building and systems, for simulation-based predictive control especially of integrated and/or competing building systems, and for other operational and maintenance purposes. In this way, the model that is used for the design of the building and systems can become a useful dynamic living document with a potentially much higher value than traditional static drawings and blueprints. Of course this would also improve the economics of building performance simulation for design purposes.

The main aim of our current project in this area is to research the model requirements for the range of applications mentioned above, and - in case the models are not the same in terms of scope and/or resolution - to research whether it will be possible to (automatically) generate the later-in-life models from the design models.

4.4 **Shared developments**

A frequently encountered problem by engineers who would like to simulate the future behavior of a design alternative is that certain performance aspects or specific building and system components are represented in one simulation environment while other performance aspects or components are only available in another simulation software. There is also no need for more programs, but there is definitively a need for better useable and more effective software. Building performance simulation is a small market; it is not interesting for the main software industry. So it is highly unlikely that there ever will be a single program that combines all necessary features.

From the above considerations it may be clear that there is a need for "open" simulation environments that would allow sharing developments in building performance simulation software. 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). This would realize the building modeling and simulation laboratory metaphor. 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. There are several strategies to enable sharing of distributed developments. The four main current strategies are discussed in the following sub-sections.

4.4.1 *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. An other 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.

4.4.2 *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 eXstensible 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.

4.4.3 *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.

4.4.4 *Data 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 run-time coupling between ESP-r and the ray-tracing lighting and visualization application Radiance.

This is possibly the most promising direction for task-shared developments. As schematically shown in Figure 6, we currently have the following three ongoing research projects in this area.

- DESIGN TOOL FOR INNOVATIVE INTEGRATED BUILDING SYSTEMS
  In terms of modeling and simulation of innovative buildings and systems (HVAC, lighting, shading, vents, operable windows, thermal storage systems, embedded renewable energy systems, etc.), two of the most restrictive shortcomings of current tools are (1) that each tool only has a limited number of systems it can represent, and (2) that inter-process communication is not possible. The main aim of this project is to research and implement (options for) inter-process communication. This, in turn, should enable run-time coupling of simulation environments and thus alleviate restriction (1) above; i.e. 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. The inter-process communication will be developed in a general sense. The result will be implemented and tested in at least three different simulation environments, two of which will be building domain specific (ESP-r and TRNSYS) and one will be domain independent (Matlab/Simulink).

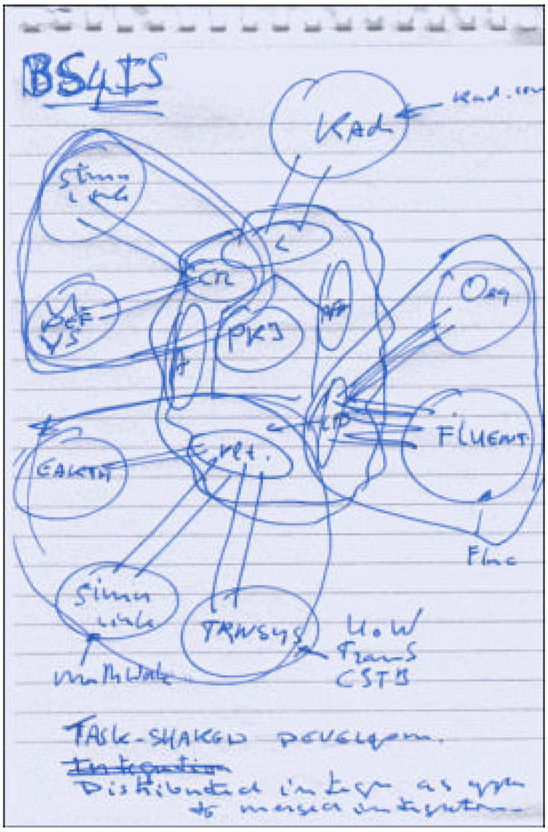

Figure 6**: Schematic view of three current projects to achieve task-shared development by data and process model co-operation**

- DESIGN TOOL FOR INNOVATIVE INTEGRATED BUILDING CONTROL STRATEGIES
  Starting from the observation that currently it is extremely difficult, if not impossible, to predict the overall effect of innovative control rules/ strategies for integrated building systems, the main aim of the project is to develop/ extend a design tool which will allow integrated performance assessment of new building control strategies. One of the shortcomings in current modeling and simulation tools is that - in terms of control - they only allow inbuilt control rules/ strategies to be assessed. However, in practice, innovative designers very often want to consider control options/ combinations not (yet) featured in the simulation environment.
  The project builds on an existing advanced building simulation research environment (ESP-r). A key feature of the new functionality will be flexibility in terms of building control definition from the user point of view. This should be achieved by 'externalizing' control definition; i.e. the user should not be restricted to control options/features on offer, but should have the option to define any control loop/strategy either by using a 'simple language' which can be understood/ interpreted by the program, or by coupling with an external control simulation program such as Matlab/Simulink.

- COUPLING BUILDING SIMULATION WITH COMPUTATIONAL FLUID DYNAMICS
  Heating, ventilation and air-conditioning (HVAC) systems often rely on low velocity air flows (eg. displacement ventilation systems, personalized ventilation systems, natural ventilation, etc.). Low velocity flows are strongly affected by thermal processes in the building. Two simulation methods are relevant for this. The first, building simulation (BSim), is an overall macroscopic approach which considers the whole of building, systems, indoor and outdoor environment over an extended period. The second, computational fluid dynamics (CFD) is a microscopic approach that focuses on heat and mass transfer processes in a single space of the building over a short period. Unfortunately, both the BSim and CFD method each suffer from shortcomings that do not exist in the other method. Examples are the dependency of the flow field solution on thermal and flow domain boundary values in CFD, and the sensitivity for convective heat transfer coefficients and air temperature stratification in BSim.
  The objective of the research is to develop and verify a proto-type co-operative BSim and CFD design environment for optimisation of building energy performance and indoor environment. The research starts from existing BSim and CFD software, and focusses on the external coupling of BSim and CFD; i.e. run-time data exchange at relevant time intervals. The main issues to be addressed are which information needs to be exchanged, at which time intervals, and by means of which data. An additional objective is to generate guidelines regarding the necessity/ applicability of BSim, CFD and the co-operative approach in terms of integrated design of buildings and systems.

All our current work starts from specific simulation environments. However, the run-time coupling mechanisms and data-exchange protocols that will be developed will have much wider and more general applicability.

The coupling mechanisms will be based on external exchange (using intermediate files or other data structures) of simulation results data. The two main advantages are that:

- any program can be coupled, provided that it has some relatively simple time step based import/export mechanism for simulation results;
- the use of intermediate data structures allows coupled programs to run on separate and even different computers in parallel.

The data to be exchanged should – as much as possible – represent physical quantities as they could be measured in the real world; i.e. as opposed to derived or abstract variables. The main advantages of this are that:

- since the data represents physical quantities, it should be readily available in different software programs;
- since such data can also be readily obtained from building energy management systems and other data-acquisition systems, it would be relatively easy to enable run-time coupling of the simulation environment with a real building (e.g. for

control purposes) or with system components in a test-rig (e.g. for hardware-in-the-loop testing).

Main research issues are:

- overall supervision and control of the separate evolution of each coupled application;
- quality assurance in terms of consistency and integrity of the overall model.

4.5 **Knowledge transfer**

The importance of modeling and simulation and how it may benefit the built environment and various stakeholder in an economical and environmental terms may be clear to the people who use this technology. However many people in the field are not yet aware of this, so there is definitely need for knowledge transfer. Two effective strategies to achieve this are as follows.

- Incorporation into the regular curricula of (higher) education, see e.g. www.bwk.tue.nl/fago/hensen
- Through organizations such as the International Building Performance Simulation Association - IBPSA, www.ibpsa.org

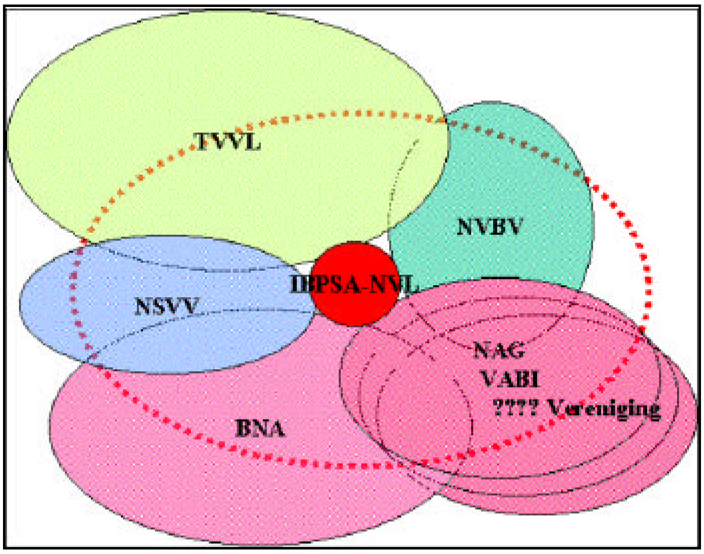

Figure 7**: Schematic of co-operation between IBPSA and professional architecture and engineering societies in Netherlands and Flanders www.ibpsa-nvl.org**

IBPSA's main role is to move this technology into everyday practice of building and systems design by increasing the awareness of the benefits, but also of the limitations and drawbacks. As indicated in Section 4.1., this technology is primarily to be used by domain specialists. Therefore IBPSA develops and maintains strong links and interactions with global and regional professional societies for architecture, heating, ventilation, air-conditioning, building physics, environmental engineering, lighting, acoustics, etc. Figure 7 is an example of how this is achieved on a regional scale.

5 CONCLUSIONS

Building performance simulation has come a long way since the early seventies. Instead of focus on the modeling aspects, there is an increasing demand for better integration of the technology in the design, construction and operation processes of buildings and the systems which service them.

Although contemporary software is able to deliver an impressive array of building performance assessments, there are many issues which hinder routine application in practice, such as (1) accuracy and confidence in the results, (2) earlier technical promises have been achieved only partly, and (3) simulation can be costly.

This paper has indicated several possible solution approaches to resolve this including (1) better quality assurance, (2) research on how to make current tools more effective in building design, (3) sharing of software developments, and (4) routes for knowledge transfer.

One of the main conclusions is that simulation is much more than just software, it is an engineering discipline which can only be applied effectively if the user has sufficient domain knowledge.

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7 SOFTWARE

Climasim	www.st.hhs.nl/~climasim
Comis	epb1.lbl.gov/comis/
EnergyPlus	www.energytools.gov/energyplus
ESP-r	www.esru.strath.ac.uk/ESP-r.htm
Ecotect	www.sq1.com
Isibat	software.cstb.fr
Matlab / Simulink	www.mathworks.com
Modelica	www.modelica.org
NMF	www.brisdata.se/nmf
Radiance	radsite.lbl.gov
Simbad	software.cstb.fr
Trnsys	sel.me.wisc.edu/TRNSYS/