

## Introduction to building performance simulation

***Citation for published version (APA):***

Hensen, J. L. M., & Lamberts, R. (2011). Introduction to building performance simulation. In J. L. M. Hensen, & R. Lamberts (Eds.), *Building performance simulation for design and operation* (pp. 1-14). Spon.

***Document status and date:***

Published: 01/01/2011

***Document Version:***

Publisher's PDF, also known as Version of Record (includes final page, issue and volume numbers)

***Please check the document version of this publication:***

- A submitted manuscript is the version of the article upon submission and before peer-review. There can be important differences between the submitted version and the official published version of record. People interested in the research are advised to contact the author for the final version of the publication, or visit the DOI to the publisher's website.
- The final author version and the galley proof are versions of the publication after peer review.
- The final published version features the final layout of the paper including the volume, issue and page numbers.

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# **1 Introduction to building performance simulation**

*Jan Hensen and Roberto Lamberts*

## **SCOPE**

The aim of this chapter is to provide a general view of the background and current state of building performance simulation as an introduction to the following chapters in this book.

## **LEARNING OBJECTIVES**

To appreciate the context, background, current state, challenges and potential of building performance simulation.

## **KEY WORDS**

Context / state-of-the-art / future needs / quality assurance

## 1.1 INTRODUCTION

Designing sustainable buildings that also fulfill all operational requirements of the users is an unprecedented challenge for our times. Researchers, practitioners and other stakeholders are faced with enormous challenges due to the need to recognize and take account of various dynamic processes around us, such as: global climate change; depletion of fossil fuel stocks; increasing flexibility of organizations; growing occupant needs and comfort expectations; increasing awareness of the relation between indoor environment and the health and wellbeing of the occupants, and consequently their productivity. Managing all of these aspects in order to achieve robust building and system solutions which will be able to withstand future demands requires an integrated approach of the subsystems, shown in Figure 1.1.

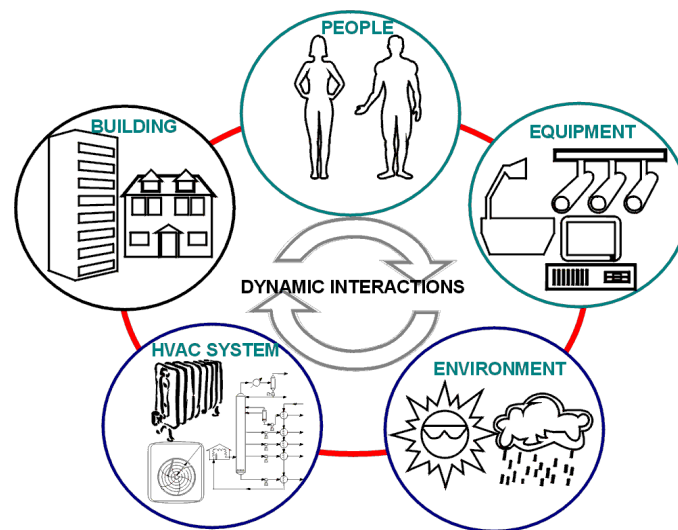


Figure 1.1. Dynamic interactions of (continuously changing) sub-systems in buildings.

In response to the sustainability challenges that we are facing, the European Union has issued the rather strict 20-20-20 initiative (relative to 1999, by 2020 20% reduction of energy consumption, 20% reduction of CO<sub>2</sub>, and 20% introduction of renewable energy. Similar and even stricter guidelines have also been developed by various countries from all over the world. Although strict, these initiatives and guidelines should be regarded as merely a first step towards the much more ambitious and demanding long-term goals as discussed in, e.g., Lund and Mathiesen (2009). Achieving these ambitious sustainability targets requires the development of net energy producing buildings or sites. For this we need models and tools which allow the consideration of interoperating domains such as transportation and large scale energy grids. Only then can the global optimization of energy production and consumption in the built environment be achieved.

In addition to these higher sustainability requirements, future buildings should also deliver considerable improvements to indoor environment quality. Rather than the current practice of merely complying with minimum standards for environmental parameters such as temperature, air quality, lighting and acoustical levels, future buildings should provide a positive indoor environment that is stimulating, healing or relaxing, depending on the function. This will then result in truly high performance buildings (Green 2009).

At present, however, the focus - even in high performance buildings - is still very much on reducing energy demand. One recent, interesting approach is to engineer a building in such a way that it can adapt itself to the actual outdoor conditions. Loonen (2010) provides a comprehensive overview of

climate adaptive building shell concepts. An illustration of a recent building with an adaptive building shell is given in Figure 1.2.



Figure 1.2. Virginia Tech Lumenhaus, Solar Decathlon 2009 hosted by the U.S. Department of Energy, National Mall, Washington, DC (Flickr 2009)

Given the relatively low volume of new building projects (in Europe only about 10% per year of the total building stock), it is evident that in order to reach the sustainability targets in time, a huge amount of work is needed in terms of refurbishment of existing buildings (see, e.g. (Petersdorff *et al.* 2006). An interesting project in this context is “Cost Effective” which aims to convert facades of existing “high-rise” buildings into multifunctional, energy gaining components (Fraunhofer 2009).



Figure 1.3. Deutsche Bank headquarters in Frankfurt am Main during refurbishment (DB Greentowers 2009)

One of the considered buildings is shown in Figure 1.3. In a holistic approach Deutsche Bank is currently creating one of the most eco-friendly high-rise buildings in the world. As one of the manifold measures the bank replaced the complete facade of an existing building with new, super-insulating triple paned windows and improved insulation. As every second window can be opened in the future, less air needs to be moved through mechanical ventilation, thanks to the natural air circulation. The project shows just how much potential for optimization and sustainable energy efficiency are possible for existing buildings as well as how a “green building” approach can be worthwhile in a wide variety of ways, even as an investment in existing properties. Energy consumption and CO<sub>2</sub> emissions of the so called Greentowers building is expected to be reduced by 89 percent (DB Greentowers 2009).

So - both new and refurbishment – future projects face huge challenges that seem too complex for current tools and approaches.

We feel that traditional engineering design tools are largely unsuitable for addressing the above challenges for the following reasons: they are typically mono-disciplinary, solution oriented and very restricted in scope. They assume static (usually only extreme) boundary conditions, and are often based on analytical methods, which to a large extent can be characterized as aiming to provide an exact solution of a very simplified view (model) of reality).

## 1.2 BUILDING PERFORMANCE SIMULATION

Computational building performance modeling and simulation<sup>1</sup> on the other hand is multi-disciplinary, problem oriented and wide(r) in scope. It assumes dynamic (and continuous in time) boundary conditions, and is normally based on numerical methods that aim to provide an approximate solution of a realistic model of complexity in the real world.

Computational simulation is one of the most powerful analysis/analytic tools in our world today – it is used to simulate everything from games to economic growth to engineering problems. However, it is very important to recognize that simulation does not provide solutions or answers, and that very often it is difficult to ensure the quality of simulation results. No matter what field they are from, those who have worked with simulation know that it is a complex task. Bellinger (2004), from the field of operational research, remarked:

–After having been involved in numerous modeling and simulation efforts, which produced far less than the desired results, the nagging question becomes; Why? ..... The answer lies in two areas. First, we must admit that we simply don't understand. And, second, we must pursue understanding. Not answers but understanding.”

As will become clear from reading the following chapters, both the power and the complexity of building performance modeling and simulation arise from its use of many underlying theories from diverse disciplines, mainly from physics, mathematics, material science, biophysics, human behavioral, environmental and computational sciences. It will also become clear that many theoretical and practical challenges still need to be overcome before the potential of building modeling and simulation can be realized.

A short historical overview of the use of simulation for building design can be found in an editorial by Spitler (2006): –Building performance simulation: the now and the not yet”. He explains that:

–simulation of building thermal performance using digital computers has been an active area of investigation since the 1960s, with much of the early work (see e.g. Kusuda 1999) focusing on load calculations and energy analysis. Over time, the simulation domain has grown richer and more integrated, with available tools integrating simulation of heat and mass transfer in the building fabric, airflow in and through the building, daylighting, and a vast array of system types and components. At the same time, graphical user interfaces that facilitate use of these complex tools have become more and more powerful and more and more widely used.”

Like many other technological developments, building performance simulation also experienced a so-called hype cycle (Fenn and Raskino 2008), as shown in Figure 1.4. The –recognition” took place in the early 1970s, with the peak of inflated expectations in the 1980s, followed by the trough of disillusionment. It seems fair to state that building performance simulation in general has been on an upward slope of productivity for almost two decades now. However, as will become clear from the following chapters, this does not appear to be the case yet for related developments such as object oriented programming, computational fluid dynamics, and building information technology.

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<sup>1</sup> Quoting Becker and Parker (2009): –It is common to see the words *simulation* and *modeling* used as synonyms, but they are not really the same thing; at least, not to those in the field bearing those words in its name. To be precise in terminology, a **simulation** enacts, or implements, or instantiates, a model. A **model** is a description of some **system** that is to be simulated, and that model is often a mathematical one. A **system** contains objects of some sort that interact with each other. A model describes the system in such a way that it can be understood by anyone who can read the description and it describes a system at a particular level of abstraction to be used.”



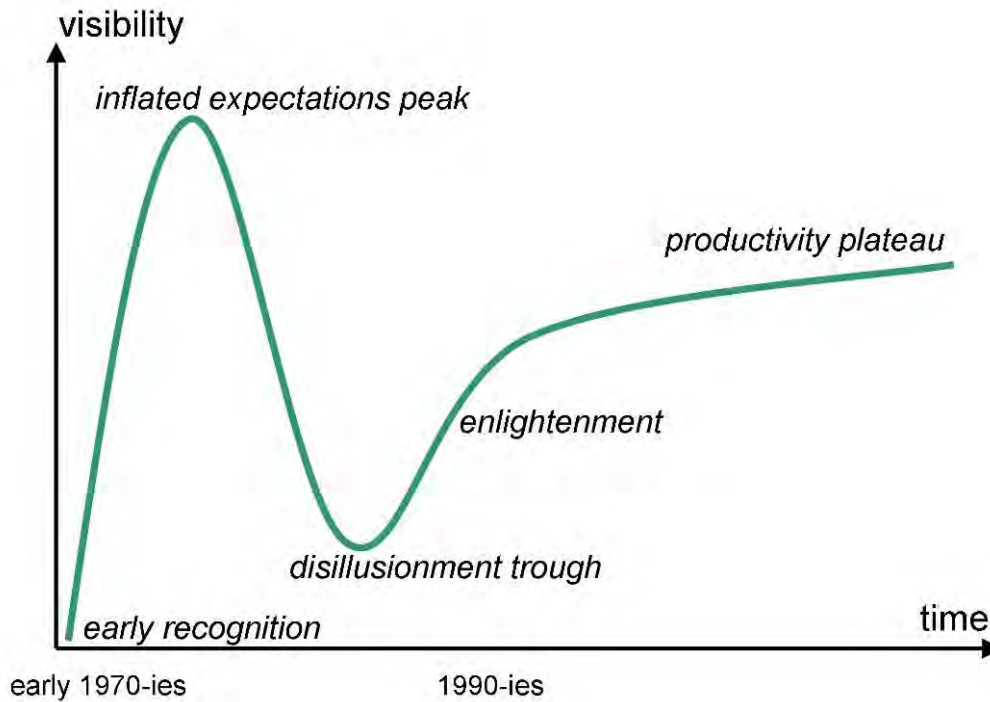


Figure 1.4. Technology hype cycle for building performance simulation

In this context, the important role of the International Building Performance Simulation Association (IBPSA - [www.ibpsa.org](http://www.ibpsa.org)) should be acknowledged, since one of its most important goals is to increase awareness of building performance simulation while avoiding both inflated expectations and disillusionment.

The following chapters demonstrate that the building simulation discipline is continuously evolving and maturing and that improvements are continually being made to model robustness and fidelity. As a result much of the discussion has shifted from the old agenda focusing on software features, to a new agenda that focuses on the effectiveness of building performance simulation in building life cycle processes.

The development, evaluation, use in practice, and standardization, of the models and programs is therefore of growing importance. This is evidenced in, for example, green building rating systems currently being promoted around the world, such as LEED (Leadership in Energy and Environmental Design) and BREEAM (Building Research Establishment Environmental Assessment Method), in incentive programs such as the US EPCAct (Energy Policy Act) and also in legislation such as the European EPBD (Energy Performance of Buildings Directive).

### 1.3 CURRENT USE IN PRACTICE

It is widely recognized that predicting and analyzing future behavior in advance is far more efficient and economical than fixing problems arising from occupant behavior when the building is in the use phase. Nevertheless, the uptake of building performance simulation in current building design practice is surprisingly limited. The actual application is generally restricted to the final phases in building design as indicated in Figure 1.5.

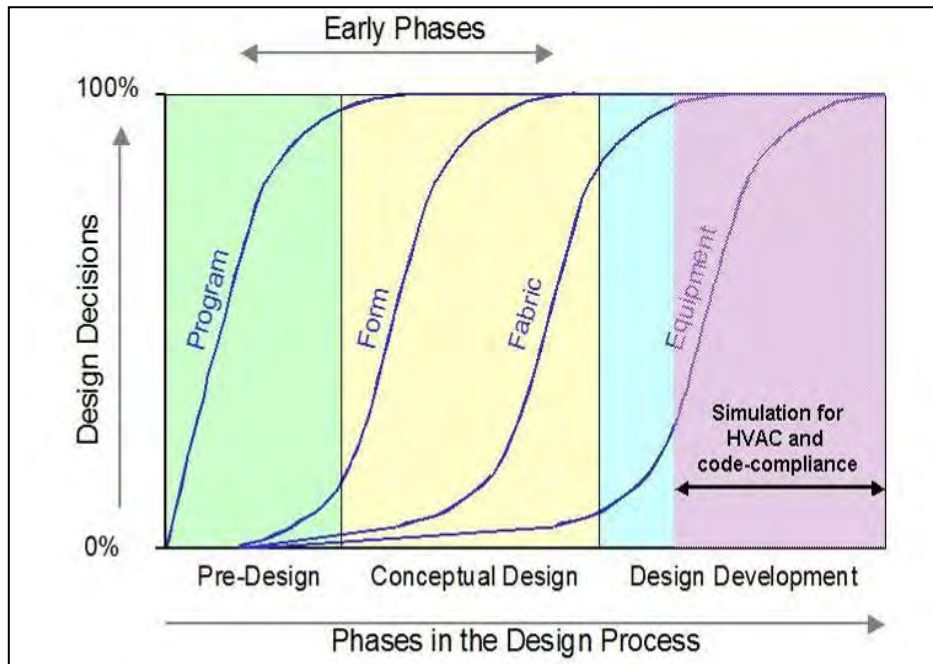


Figure 1.5. Current use of performance simulation in practical building design. (Source: Torcellini and Ellis 2006)

At present, in addition to its relatively low adoption, the use of building performance simulation is largely restricted to a few key areas: for building envelope design; to predict risk of overheating during the summer (Figure 1.6 shows a typical example) and/or to calculate maximum cooling loads in view of equipment sizing (Figure 1.7 and 1.8 as example).



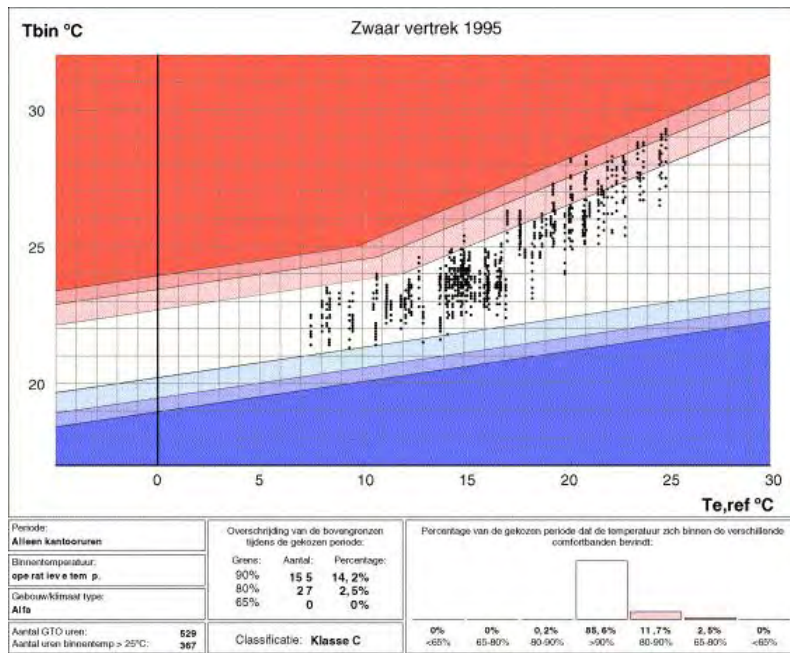


Figure 1.6. Output visualization of adaptive thermal comfort predictions for a medium-heavy office building in The Netherlands during the period from May to end September 1995. (Linden *et al.* 2006)

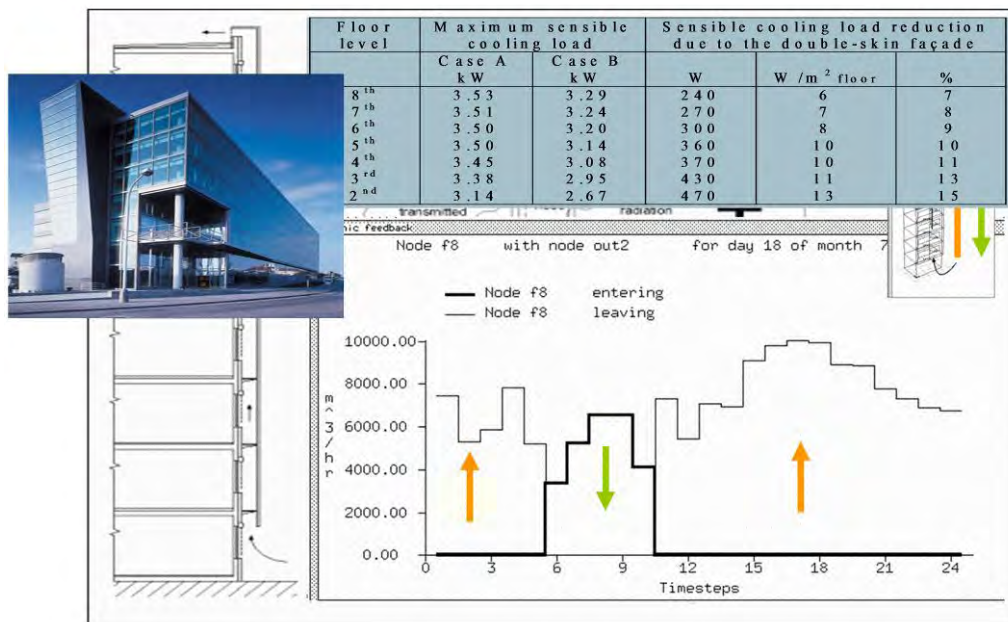


Figure 1.7. Sample airflow and cooling load simulation results for an office development in Prague with double-skin façade. (Hensen *et al.* 2002)

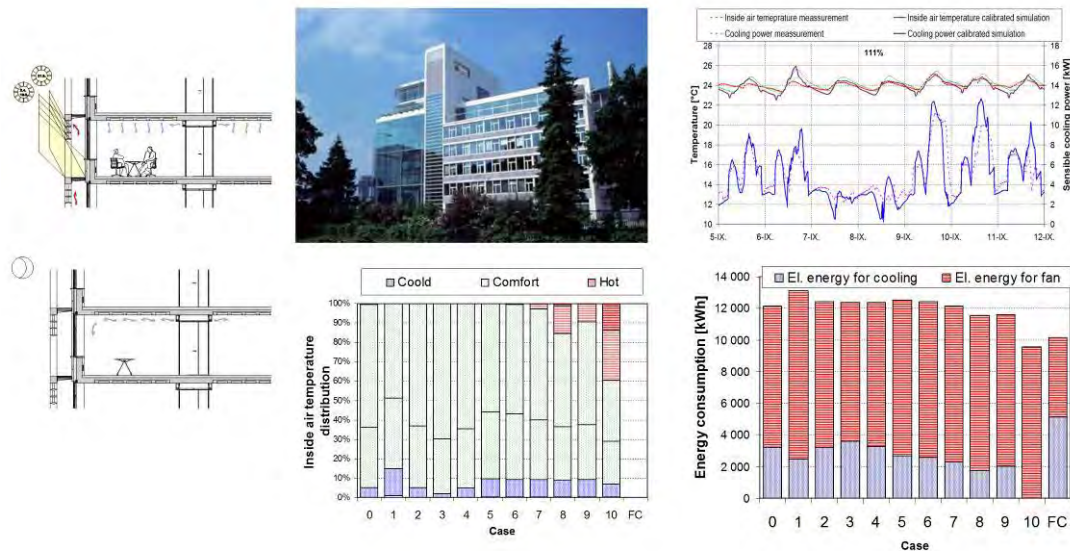


Figure 1.8. Sample comfort, cooling load and energy simulation results for a low-energy office building in Prague where 10 different system operational scenarios have been compared using building + systems models which were calibrated with real scale experimental results (Lain *et al.* 2005)

Although Figure 1.8 is from a study where simulation was used for mechanical engineering design, in reality these sorts of studies are rare. It is still much more common to see traditional design approaches being used for this. Thomas (2006) clearly demonstrates this point:

—Out of a typical large mechanical-electrical (M-E) design project consisting of 50,000 HVAC<sup>2</sup> labor-hours, about 100 hours is spent on energy analysis. Another 200 hours might be spent on loads calculations over the course of the project. This is about the total extent of HVAC engineering design using computer programs today. The remaining 99.9% of computer use is for drafting, word processing and spreadsheets for organizing information. The same is true for electrical, lighting, plumbing and fire protection design.

The M-E design process is fragmented, equipment selection and scheduling is intermittent and the process consists of frequent revisions and continuous exchange of fragmented information between specialized architectural and engineering personnel. A-E design documents from schematic to construction are issued in 2-D whereas the new automated systems are in 3-D. The present organizational structure and specialized staff and tasks will not work well with these new advanced systems. There has to be a change in the A-E design culture.”

To recap/summarize: in current practice building performance simulation is largely restricted to the analysis of a single design solution. The potential impact of building simulation would be greatly enhanced if its use was extended to (multiple variant) design optimization and included much earlier in the design process. . To illustrate this point, consider the CIBSE (2005) design strategy for environment friendly and future proof building design, which can be summarized in the following sequential steps:

1. Switch off – relating to internal and external thermal loads
2. Spread out – use thermal mass
3. Blow away – apply (natural) ventilation when possible

<sup>2</sup> Heating, Ventilation and Air-Conditioning

- Cool when necessary – do not hesitate to include some extra (mechanical) cooling in order to be prepared for future climate change

The effects of the three first approaches depend mainly on design decisions related to building program, form and fabric, and can only be predicted by simulation. The same is true for another – more or less corresponding – design strategy known as Trias Energetica (Lysen 1996), which involves, in sequence and order of importance, the following steps:

- Reduce energy demand by implementing energy-saving measures and optimize the use of solar and casual gains;
- Use sustainable sources of energy instead of finite fossil fuels;
- Use fossil energy as efficiently as possible.

Again, the decisions related to the first step are taken primarily during the early design phases, and as such the impact/ performance can only be predicted by simulation.

Moving beyond the design phases, there exists a considerable and rapidly increasing interest - in practice and research - in the use of simulation for post-construction activities such as commissioning, operation and management. The uptake in current practice is still very limited, but we expect that the next decade will see a strong growth in application of building performance simulation for such activities. The two main reasons for this are (1) the current (considerable) discrepancy between predicted and actual energy consumption in buildings, and (2) the emergence of new business models driven by whole life time building (energy) performance.

Although a large number of building performance simulation tools exist (DOE 2010), it is also clear (e.g. from Crawley *et al.* (2008)) that there is a huge overlap in functionality amongst many of these tools. In various fields, including building and system design, people can be classified according to their innovativeness (Figure 1.9). From interviews with building and system designers (Hopfe *et al.* 2006) it was found that someone can be classified as an innovator in one aspect (say use of simulation tools) while belonging to the “late majority” in another aspect (say in terms of design team integration). A major requirement of an innovator would be that the simulation tool can be used to model and simulate all sorts of (not yet existing) building systems and applications. For that type of person it would not matter much if the tool would be quite hard to learn and use as long as it is very flexible and expandable. For the “late majority”, on the other hand, it is essential that the tool appears intuitive and easy to use. This variety in needs combined with the relatively low potential number of software copies to be sold, remains a huge challenge for commercial software developers.

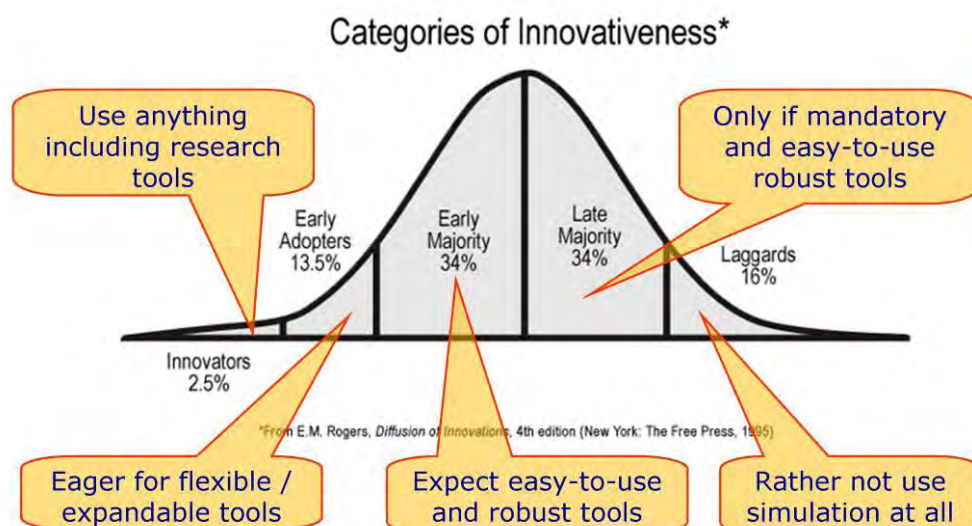


Figure 1.9. Attitude and expectations regarding simulation tools in relation to the (design) innovativeness of the user. (Adapted from Rogers (1995))



## 1.4 QUALITY ASSURANCE OF SIMULATION BASED DECISIONS

Quality assurance is a very important and ongoing issue addressed throughout this book. The quality of simulation results depends, of course, on the physical correctness of the model. Although Robinson (1999) is not related to building simulation, the conclusion that it is not possible to validate a model and its results, but only to increase the level of confidence that is placed in them, seems to be equally true for our domain. The ongoing BESTEST initiative (e.g. Judkoff and Neymark (1995); Neymark *et al.* (2001)) represents a major international effort within the building domain to increase the confidence of simulation results. Its progress is reflected in its first footholds in professional standards such as the American Society of Heating Refrigerating and Air-Conditioning Engineers (ASHRAE) Standard Method of Test 140.

It is worth noting that it is still common practice not to report confidence levels for simulation results. This is interesting because it is well known that, for example, real and predicted energy consumption of low-energy buildings is extremely dependent on uncertainties in occupant behavior; as illustrated in Figure 1.10.

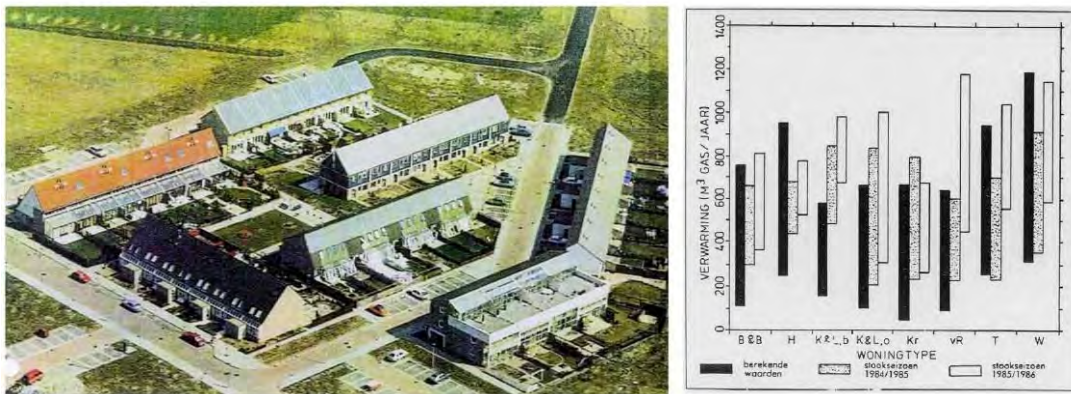


Figure 1.10 Variability in predicted gas use for space heating (black bars) in eight different types of Dutch low-energy houses due to uncertainties in occupant behavior in terms of heating set-point, casual gains and infiltration rates, compared to measured values for 1984-1986 heating seasons (Hensen 1987)

User and use related aspects are very often under-appreciated in building performance simulation. In terms of application, for example, simulation is much more effective when used to predict the relative performance of design alternatives, than when used to predict the absolute performance of a single design solution.

In practice it can also be commonly observed that complex high resolution modeling approaches (such as computational fluid dynamics (CFD)) are used for applications where a lower resolution method would be quite sufficient and much more efficient. There is also a wide-spread misconception that increasing the model complexity will decrease the uncertainty of the results. As indicated in Figure 1.11, in reality, deviation from the optimum to either lower or higher complexity increases the potential error in the simulation results.

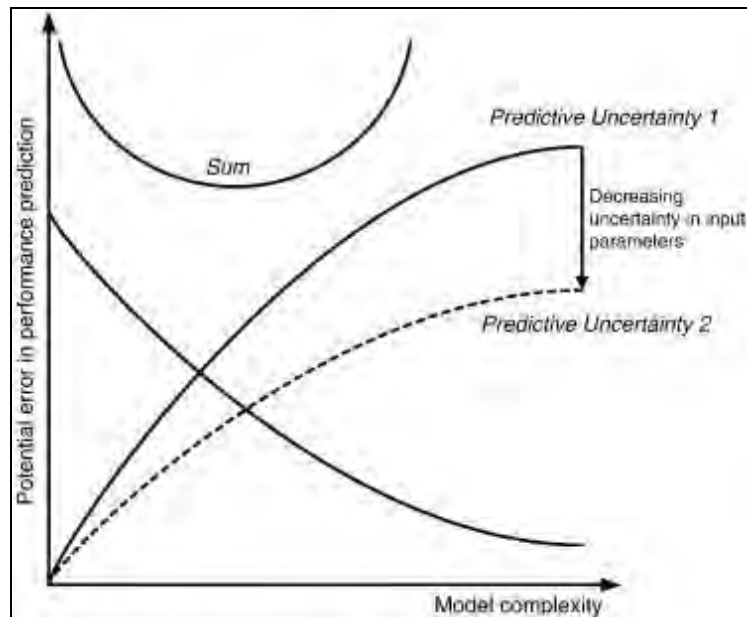


Figure 1.11 Potential error in performance prediction vs. model complexity/ level of detail (Trcka and Hensen 2010)

The above discussion is an element of conceptual modeling, i.e. the process of abstracting a model of a real or proposed system. Robinson (2008) states that

—All simulation models are simplifications of reality.... The issue in conceptual modelling is to abstract an appropriate simplification of reality..... The overarching requirement is the need to avoid the development of an overly complex model. In general, the aim should be: to keep the model as simple as possible to meet the objectives of the simulation study.”

The implication of this is that for the same physical artifact (e.g. a building, a façade or an HVAC component) a different modeling approach is to be preferred depending on the objective of the simulation. Hensen (2004) elaborates on this for building airflow related performance studies.

From the above it must be clear that the primary and paramount requirement for quality assurance is sufficient domain knowledge by the user. According to Becker and Parker (2009), we should nevertheless appreciate the distinction between being a subject matter expert in something, being able to describe that thing so it can be simulated, and actually implementing and testing the simulation.

There is a lot to be learned from modeling and simulation in other domains, especially with respect to methodological aspects. Banks and Gibson (1997), for example, relates to electrical engineering, but it is remarkable that there are many cases in our domain in which one or more of their rules —when not to simulate” are applicable. In summary, they say that simulation is not appropriate when:

1. The problem can be solved using "common sense analysis—
2. The problem can be solved analytically (using a closed form)
3. It's easier to change or perform direct experiments on the real thing
4. The cost of the simulation exceeds possible savings
5. There aren't proper resources available for the project
6. There isn't enough time for the model results to be useful
7. There is no data – not even estimates
8. The model can't be verified or validated



9. Project expectations can't be met
10. System behavior is too complex, or can't be defined.

It also seems worthwhile to consider the application methodology from Banks and Gibson (1996) which involves the following sequential steps:

- Step 1: Define the problem
- Step 2: Understand the system
- Step 3: Determine your goals and objectives
- Step 4: Learn the basics
- Step 5: Confirm that simulation is the right tool
- Step 6: Attain support from management
- Step 7: Learn about software tools for simulation
- Step 8: Determine what data is needed and what is available
- Step 9: Develop assumptions about the problem
- Step 10: Determine the outputs needed to solve the stated problem
- Step 11: Simulation will be conducted internally or externally?
- Step 12: Kickoff the project

## 1.5 DISCUSSION

As a (future) simulator, please note that simulation is a skill that needs to be learned. The first step is to acquire sufficient domain knowledge, and then skills and knowledge relating to principles, assumptions and limitations of modeling and simulation. Only with this combined knowledge it will be possible to determine when and when not, to use simulation.

In the context of user aspects of quality control it is very good to see that professional organizations such as ASHRAE and the Illuminating Engineering Society of North America (IESNA) are collaborating with IBPSA to develop an Energy Modeling Professional certification program. The purpose of this certification is to certify individuals' ability to evaluate, choose, use, calibrate, and interpret the results of energy modeling software when applied to building and systems energy performance and economics and to certify individuals' competence to model new and existing buildings and systems with their full range of physics.

## SYNOPSIS

This chapter demonstrates that building performance simulation has the potential to deliver, directly or indirectly, substantial benefits to building stakeholders and to the environment. It also explains that the building simulation community faces many challenges for the future. These challenges can be categorized in two main groupings:

- Provide better design support; issues here include early phase design support, multi-scale approaches (from construction detail to district level), uncertainty and sensitivity analysis, robustness analysis (employing use and environmental change scenarios), optimization under uncertainty, inverse approach (to address “how to” instead of being able to answer “what if” questions), multi-physics (particularly inclusion of electrical power flow modeling), and integration in the construction process (using building information modeling (BIM), process modeling, etc)
- Provide support for building operation and management, with issues such as accurate in-use energy consumption prediction, whole building (total energy) performance analysis, model predictive (supervisory multi-input multi-output control)

Many (but not all) of these issues are addressed in the following chapters.

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## RECOMMENDED READING

We recommend that you read the rest of this book, but not necessarily from the beginning to the end. Read the chapters according to your personal interest. This book aims to provide a comprehensive and in-depth overview of various aspects of building performance modelling and simulation, such as the role of simulation in design, outdoor and indoor boundary conditions, thermal modelling, airflow modelling, thermal comfort, acoustics, daylight, moisture, HVAC systems, micro-cogeneration systems, building simulation in operational optimization and in building automation, urban level modeling and simulation, building simulation for policy support, and finally a view on future building system modelling and simulation.

The structure of each chapter is the same. It starts with identifying the scope and learning objectives. This is followed by introduction, scientific foundation, computational methods, application examples, discussion, and synopsis. As we are limited by to space constraints, each chapter includes recommendations for further reading. In order to practice what has been learned, each chapter finishes with some suggested activities or assignments.

## ACTIVITIES

After reading (parts of) this book, please email your feedback to [j.hensen@tue.nl](mailto:j.hensen@tue.nl) and [lamberts@ecv.ufsc.br](mailto:lamberts@ecv.ufsc.br) .