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1 Building performance simulation – challenges and opportunities

Jan Hensen and Roberto Lamberts

SCOPE

The aim of this chapter is to provide a general view of the context 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

INTRODUCTION

Building performance covers a wide variety of aspects. In the past and for the immediate future much attention is rightfully devoted to energy efficiency of buildings and communities. However, it is vitally important to realize that the primary purpose of buildings is to protect against undesirable outside conditions, and in the case of commercial buildings and homes, to provide healthy, comfortable and also, in many cases, productive indoor environments. Awareness of the significant potential benefits of providing these features is rapidly increasing; see Figure 1.1. As such, it can be expected that indoor environmental quality for health and well-being will arguably become more important than energy related performance in the not so distant future.

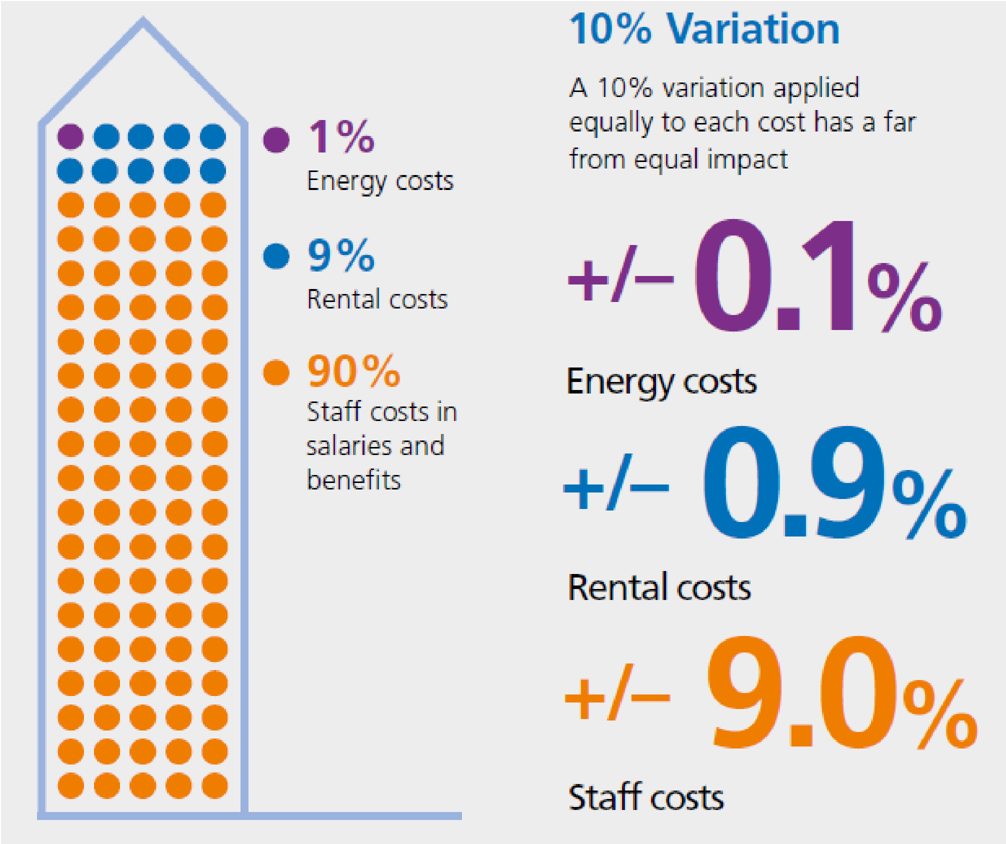

Figure 1.1. Typical business operating costs and the effect of a 10% variation applied to each cost (WGBC 2014)

From the perspective outlined above, building energy performance should not be addressed as an objective in itself, but rather as a cost function. Other important challenges that the built environment must manage include:

- The range of scale from tiny to enormous buildings
- The range of construction from "do it yourself" to industrial
- The idiosyncrasy of bespoke buildings that present unique challenges in the design, building and operational phases
- The wide variety of stakeholders in the built environment with varying and often conflicting interests
- The necessity for building designs to compromise or optimize depending on available resources and (conflicting) stakeholder "wishes"
- The expected longevity of buildings and their future uses
- The increasing complexity of buildings and integrated building systems
- The increasing interconnectedness of buildings at the local and district levels
- The change from energy consumer to energy prosumer
- …

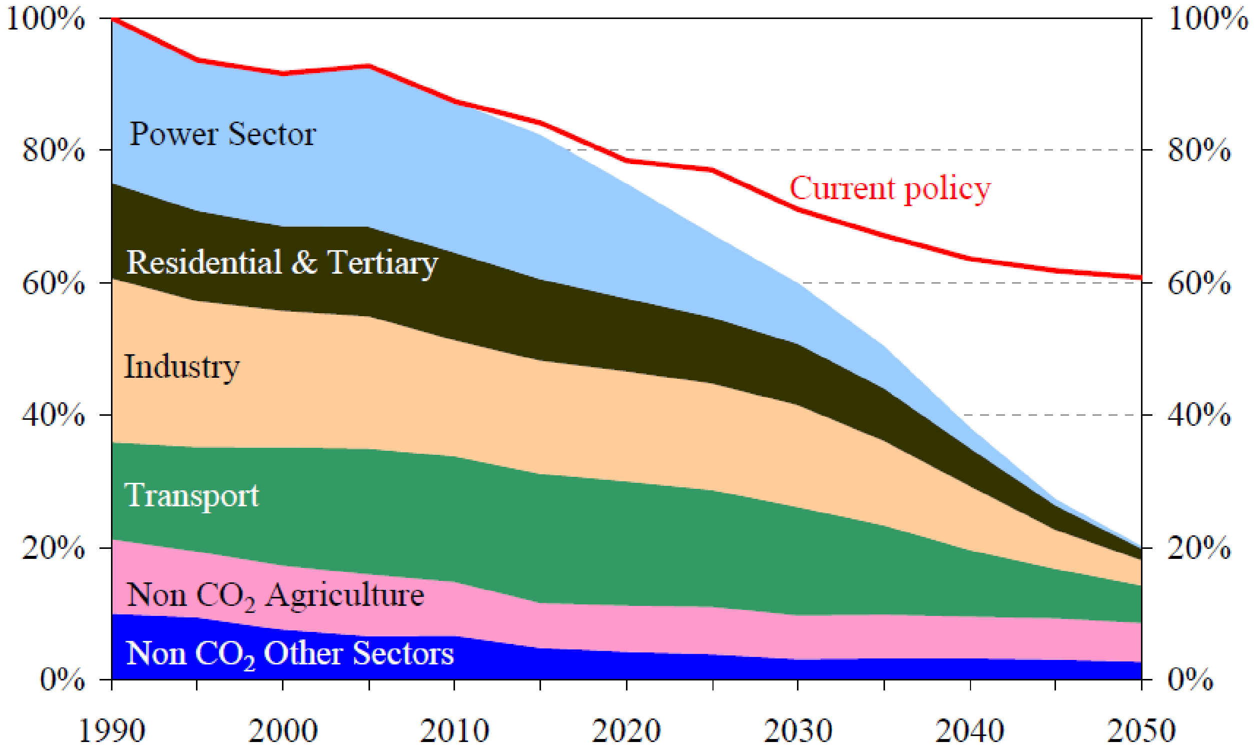

Figure 1.2. EU GHG emissions towards an 80% domestic reduction (EU 2011)

Despite the above discussion, immediate legislative pressures have placed decarbonization of the energy supply for residential and tertiary sectors high on the agenda. At present, fossil fuel consumption of buildings is responsible for a considerable portion of the total CO2 emissions. The EU low-carbon economy roadmap (EU 2011) suggests that by 2050, the EU should cut greenhouse gas emissions to 80% below 1990 levels. Important milestones on the way to achieving this target are 40% emissions cuts by 2030 and 60% by 2040. As indicated in Figure 1.2 the current policy will not have the desired effect, and thus all sectors will need to contribute and collaborate where necessary.

For the building sector this implies the need to contribute many innovative building solutions such as: building-integrated electricity production, energy storage systems, adaptive building skins, switchable glazing, super-insulation, demand response, etc. Furthermore, these innovative solutions must be thoroughly tested to understand how they can be integrated into existing buildings or combined and optimized in new designs, and to determine how robust they may be to future scenarios.

Thus, the ultimate challenge for the building sector is to achieve a zero-carbon built environment by designing and developing high-performance buildings with indoor environments optimized for health, comfort and/or productivity. To face such a complex challenge, expertise is required from many different technical and non-technical disciplines. This expertise should be integrated and managed in a multi-actor, multi-scale, multi-physics and performance-based approach.

We believe that computational building performance modeling and simulation potentially offers huge opportunities in this endeavor.

BUILDING PERFORMANCE SIMULATION

Computational modeling (i.e. creating a computer-based representation of a real system at a particular level of abstraction) and simulation (i.e. enacting, or implementing, or instantiating, a model to predict the (future) behavior of a real system) is one of the most powerful and widely used analysis techniques, with applications ranging from economic and climate forecasting to the testing of games and engineering problems. Nevertheless, it is very important to recognize that (1) simulation does not directly generate solutions or answers – its main purpose is to increase understanding, and that (2) most of the time it is difficult to ensure the quality of simulation results.

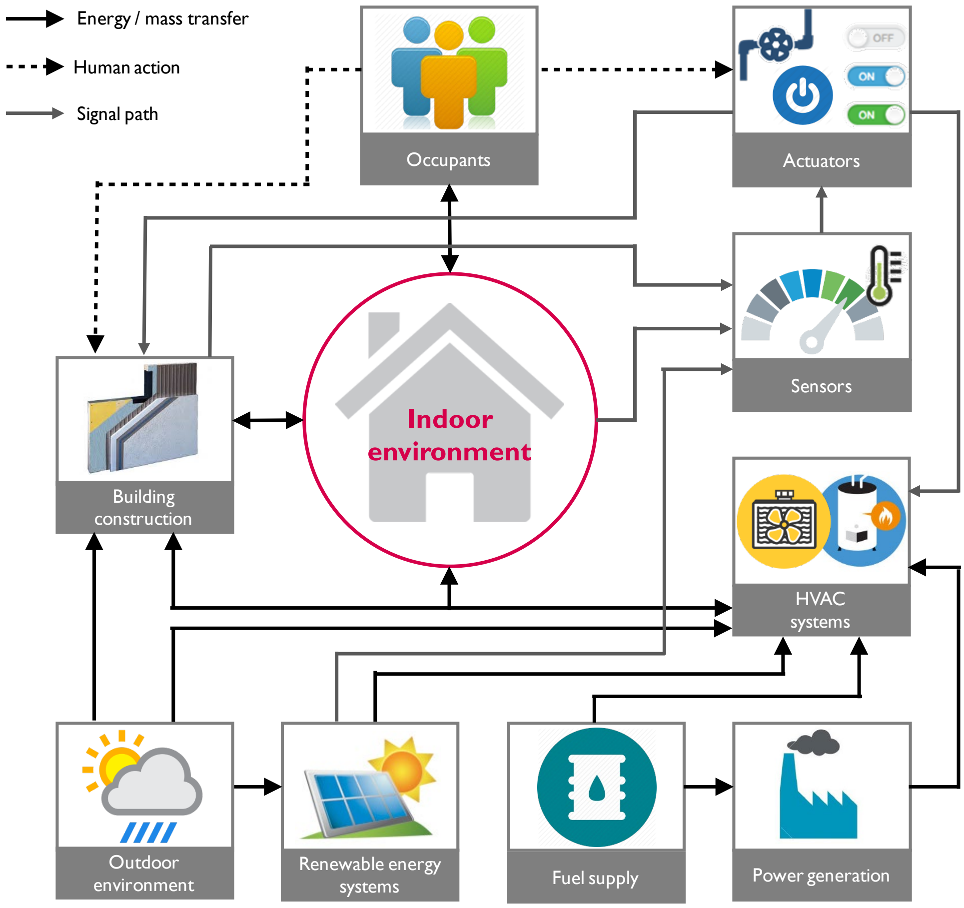

Figure 1.3. Dynamic interactions of (continuously changing) sub-systems in buildings

Computational building performance modeling and simulation primarily covers the aspects sketched in Figure 1.3. Research, development and application of building performance simulation started in the 1960s. For reviews of the history and current state of building performance simulation, see e.g. Kusuda (1999), Spitler (2006), Clarke & Hensen (2015) and/or Wang & Zhai (2016). Over time, numerous building energy software tools have been developed; see BEST (2018).for an overview of currently available tools.

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. The fidelity and robustness of simulation models has improved significantly, and is set to continue.

The proliferation of activities and publications of the International Building Performance Simulation Association (IBPSA – http://www.ibpsa.org) provides ample evidence that the discipline of building performance simulation is continually evolving and maturing.

Whereas in the early days of simulation the main agenda focused on modeling and software features, the discussion has moved in recent decades to the effectiveness of building performance simulation in building life-cycle processes. The development of powerful and user-friendly interfaces has resulted in the wide use of building performance simulation. Nevertheless, many theoretical and practical challenges still need to be overcome before the full potential of building performance modeling and simulation can be realized.

One of the aims of this book is to demonstrate that building performance simulation can be used for many different applications. At present, there is a growing acceptance that modeling and simulation has an important role to play in the development of new or renovated, high-performance sustainable buildings.

Other application areas are not directly related to design or operation of a particular building or district but serve more general objectives, such as policy support (see Chapter 12). Similarly, modeling and simulation has an important role in the development of novel building systems and components (see e.g. Loonen et al. 2017)).

There also 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 limited, but we expect that the next decade will see strong growth in the 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 (see e.g. De Wilde 2014), and (2) the emergence of new business models driven by whole life time building (energy) performance.

Another area that has gained considerable interest recently is that of urban modeling and simulation, which is why this 2nd edition book now includes no less than three chapters on this topic.

QUALITY ASSURANCE OF SIMULATION BASED DECISIONS

Quality assurance of simulation based decisions – not only for design, but for all sorts of applications - is a very important and ongoing issue addressed throughout this book. So, in this introductory chapter we limit ourselves to some general aspects.

Firstly, the quality of simulation results depend, 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. Secondly – and likely even more important – quality assurance of results for simulation based decisions depends on much more than only the physical correctness of the model; the quality of the end result (ie. the results to be communicated to decision makers) can only be "assured" when it is based on quality assurance during all steps of a simulation study.

In other words, while the correctness of the model may be thought of as having the greatest influence on the credibility of simulation results, the accuracy of the problem formulation is also a greatly influential factor that must be properly considered. Accordingly, it is crucial to begin employing validation, verification, and testing (VV&T) techniques in this first phase and continue to employ them over the full life cycle of the simulation study, which culminates in the presentation of the results. Such a VV&T procedure is very eloquently described by Balci (1994).

The difference between verification, validation and testing is as follows. Model verification aims to identify any inaccuracies that may arise and discover any errors in the model when it undergoes transformation from one form to another. Model verification deals with <u>building the model right</u>. Model validation aims to substantiate that the behaviour of the model is accurate, consistent and in line with the objectives of the study in the chosen target domain. In essence, model validation governs the process of <u>building the right model</u>.
Model testing is conducted to identify any inaccuracies that may exist and to reveal errors within the model. Testing of the model involves the input of test data or test cases, which is then evaluated to see if the model functions correctly and as expected. If this testing returns the result of "test failed", this implies failure in the model and not in the test. Validation and verification are the dual reasons that such testing is performed. Testing that aims to validate is primarily concerned with evaluating the model's behavioural accuracy, while verification tests are focused on determining the accuracy of the transformation of the model from one form to another. VV&T is used as a term to capture the entirety of these testing processes.

Model VV&T serves to safeguard against three key error types associated with simulation applications (Balci 1990). The Type I Error occurs when the credibility of the model is incorrectly deemed to be unacceptable. In contrast, the Type 2 Error occurs when the credibility of the model is incorrectly deemed as acceptable. The Type 3 error occurs when a model solves a problem other than the problem of interest. The terms 'Model Builder's Risk' and 'Model User's Risk' are used to refer to the risk of committing Type 1 and Type 2 errors, respectively. The result of committing Type 1 errors is that the model development will increase in terms of cost. However, the results of Type 2 and Type 3 errors may well render the simulation study useless and decisions based on its results may have major negative consequences.

The life cycle of a simulation study is presented in Figure 1.4. The phases are depicted by the shaded ovals. The relations between the phases are represented by the dashed arrows. The credibility assessment stages are depicted by the solid arrows. It should be noted that the dashed arrows do not imply that the life cycle can be seen as a rigidly linear or sequential process. Rather, these dashed arrows simply indicate the general direction of travel through the development life cycle. Another noteworthy point is that there is an associated VV&T activity for each life cycle phase. Negative results from any of these activities may lead to the need to revisit an earlier phase or even to begin the process afresh. VV&T should not be seen as a set of discrete phases or steps within the life cycle; it should be seen as a continuous set of actions that take place during the entirety of the life cycle phases.

The phases can be grouped in three categories as follows. The problem definition phases deal with the communicated problem, formulated problem, proposed solution technique and system and objectives definition. The model development phases consist of all the phases depicted in the circle in Figure 1.4. The decision support phases consist of the simulation results and integrated decision support phases.

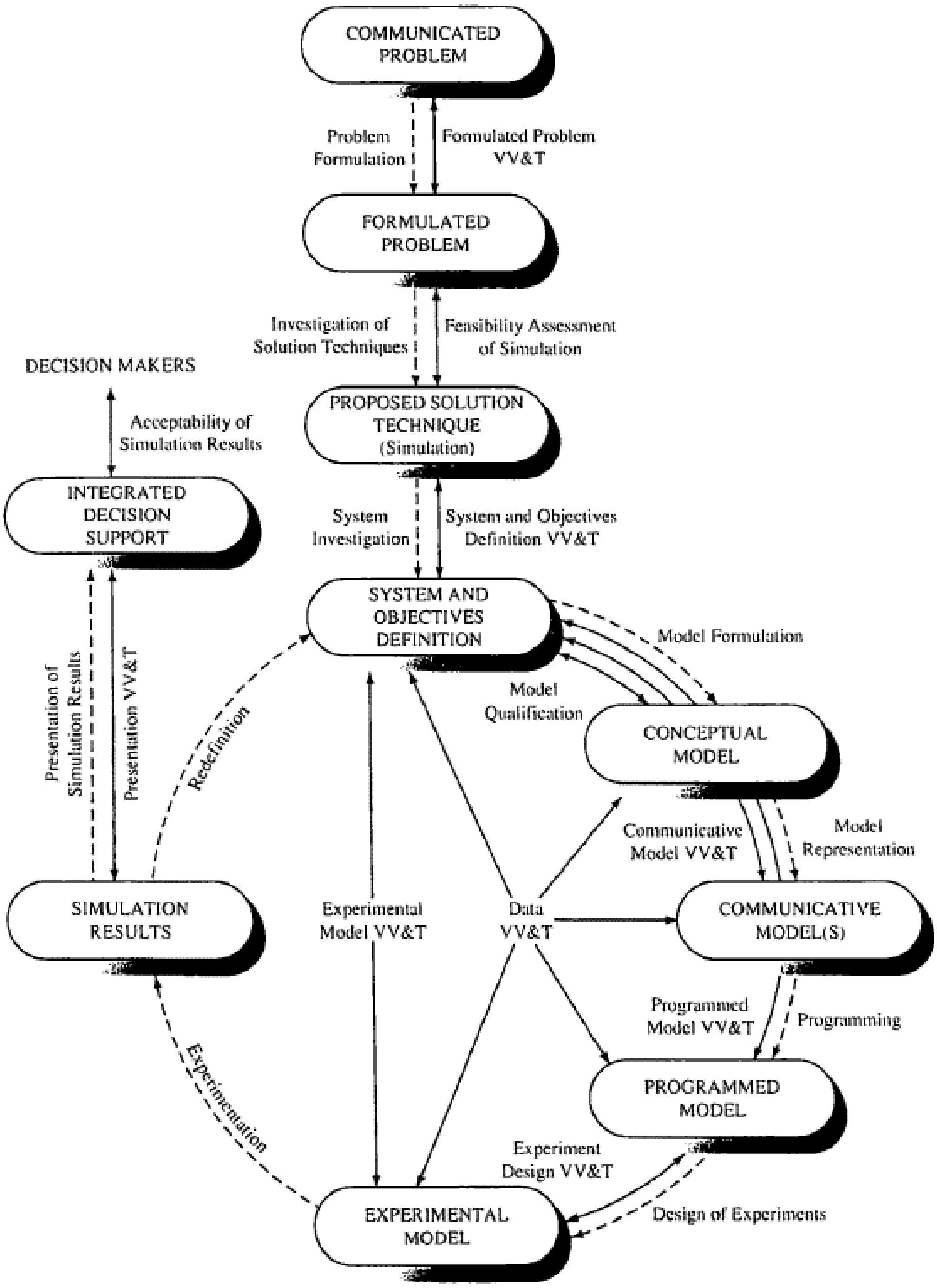

Figure 1.4. Verification, validation and testing throughout the life cycle of a simulation study (Balci 1994)

Conducting VV&T activities across the full life cycle is done with the purpose of identifying shortcomings in quality in any phase of the study. These activities, then, act as safeguards from the inception of the project, when the problem is communicated, until project completion, when the results of the implemented simulation are presented.

Although most studies are initiated by a decision maker in response to a recognized problem, this problem is rarely defined with sufficient clarity and specificity to enable an analyst (problem-solver/consultant/research group) to immediately begin working towards a solution. Generally, an essential first step is to carefully formulate the problem as precisely and accurately as possible. This problem formulation should function to allow the analyst to proceed by conceiving of specific and appropriate research endeavors.

A clear problem formulation allows the analyst to identify alternative techniques capable of addressing the formulated problem. These techniques should then be evaluated and those that are determined to cost too much in terms of time or money, or those that are deemed to be unable to yield sufficient benefits in terms of the given objectives should be discarded. The analyst should then weigh the remaining techniques against each other to determine which will yield the greatest benefit-cost ratio. this selection procedure of available techniques underlines the point that it is unwise at best and invalid at worst to rely on the aphorism "when all else fails, use simulation". If used, simulation must be shown to the decision maker to be a credible solution to the problem at hand.
Here, it is worth to consider the "ten reasons why not to simulate" by Banks and Gibson (1997), which can be summarized as:
Don't simulate 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.

In the conceptual and communicative model phases one has to decide about the modeling complexity, which includes the scope (how much of the real world is represented) and resolution (number of variables in the model and their spatial and temporal precision or granularity). In this context it is advisable to adhere to Occam's Razor or Einstein's principle, which imply that a model should be as simple as possible but not simpler. Thus, as Robinson (2008) points out:
"All simulation models are simplifications of reality…. The issue in conceptual modeling 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 this for building airflow related performance studies.

It is "interesting" to note that the majority of validation and verification efforts in our field are restricted to the programmed model phase depicted in Figure 1.5. Very few publications address VV&T during the other phases of a simulation study. However, it can be expected that in our field, like in many others, numerous issues could arise from poor/absent VV&T in the other phases – starting with the communicated problem and ending with the decision support phase.

It is also "interesting" to note 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 and weather, to just mention two aspects.

Further explanation and details of the life cycle application of VV&T can be found in (Balci 1994). Here it suffices to state that conducting VV&T activities is of paramount importance in guiding complex, large-scale simulation applications to an efficacious end. It is crucial that the importance of VV&T is understood by all stakeholders in the process, including those sponsoring the study and those conducting it. Even though its importance is clear, implementing VV&T across all project phases costs a great amount of time and effort. In real applications in which the simulation study is often limited by the available time, documentation of VV&T activities is sometimes necessarily jettisoned. In order to remedy this less than ideal situation, further research attention is needed to determine how best to provide computer-aided assistance so that VV&T techniques can be automated within applications of building performance simulation.

From the above it is hopefully also clear that the primary and paramount requirement for quality assurance is sufficient domain knowledge of 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.

DISCUSSION

As a (future) simulator, please note that simulation is a skill that needs to be learned. As implied above, 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 domain and simulation knowledge will it be possible to assure the quality and have conficence in the eventual results. When learning about modeling and simulation it is important to do that step by step, and thus moving from less to more complex tools, as explained in the "Black belt energy modeling matrix" by Franconi (2010).

In the context of user aspects of quality control, it is very encouraging to see that professional organizations such as ASHRAE and CIBSE are collaborating with IBPSA to bring this to the attention of professionals. Both ASHRAE and CIBSE have many publications related to theoretical and practical aspects of building performance simulation. ASHRAE now also has an Energy Modeling Professional certification program. The purpose of this certification is to certify an individual's 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 present and future challenges. These challenges can be categorized in two main groupings:

- Provide better decision support; issues here include product development support, policy support, 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 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

(1) In case you are not yet an IBPSA member, we strongly advise you to check out www.ibpsa.org. There is a good chance that there is already a group of like-minded people in your region. In case you are interested in regular updates of what is going on in the building performance simulation field, make sure that you sign up for IBPSA News.
(2) In case you are interested in leading edge research in this field, we recommend to look up the Journal of Building Performance Simulation which aims to make a substantial and lasting contribution to the international building community by supporting authors and the high-quality, original research they submit. This journal also offers a forum for original review papers and researched case studies.
(3) We are very keen to know your opinion about this book. So, after reading (parts of) this book, please email your comments, suggestions or other feedback to j.hensen@tue.nl and lamberts@ecv.ufsc.br .