Building performance s(t)imulation

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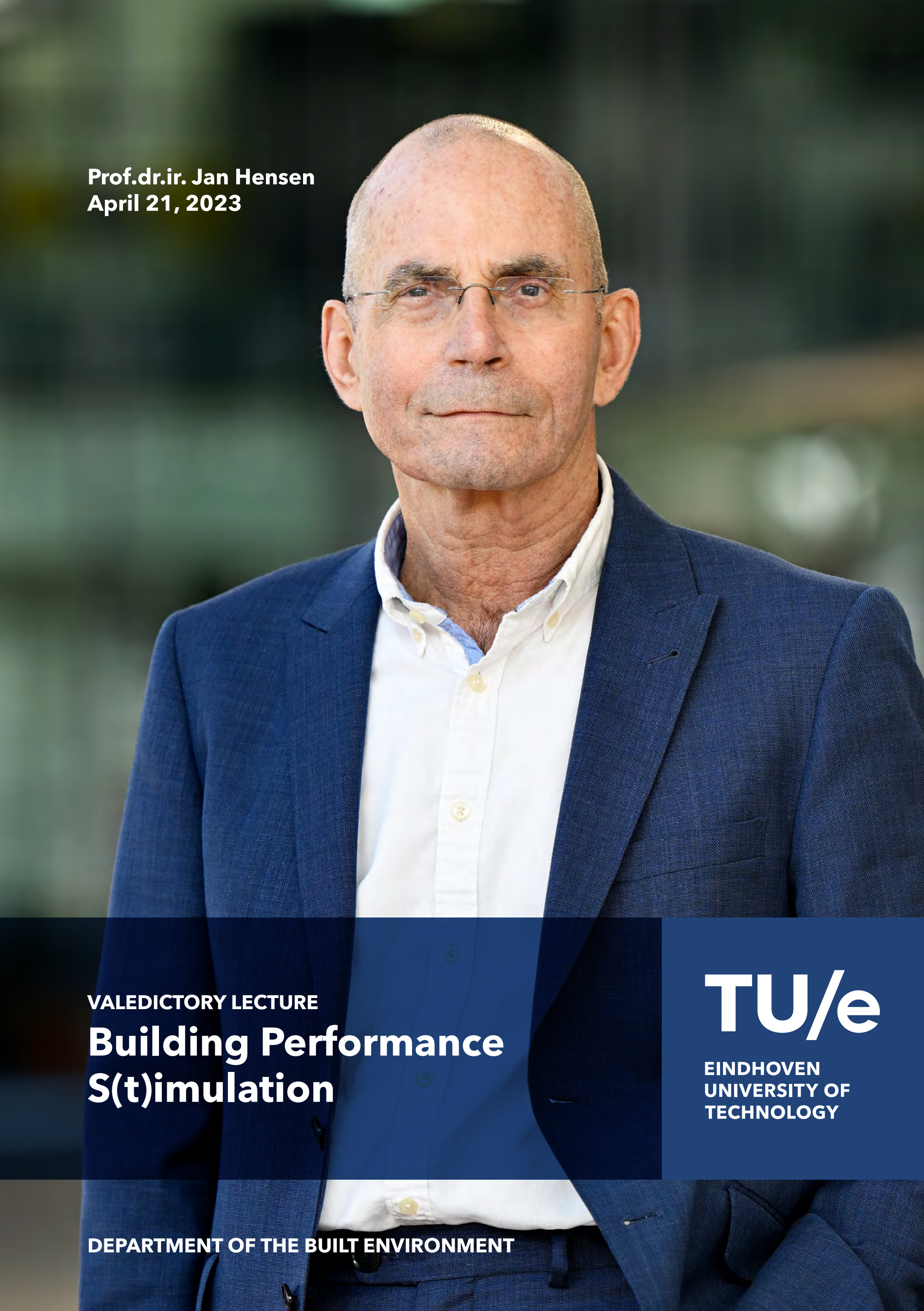


Prof.dr.ir. Jan Hensen
April 21, 2023

VALEDICTORY LECTURE

Building Performance S(t)imulation

EINDHOVEN UNIVERSITY OF TECHNOLOGY

DEPARTMENT OF THE BUILT ENVIRONMENT

VALEDICTORY LECTURE PROF.DR.IR. JAN HENSEN

Building Performance S(t)imulation

Presented on April 21, 2023
at Eindhoven University of Technology

Introduction

Mijnheer de Rector Magnificus, leden van het College van Bestuur van de
Technische Universiteit Eindhoven, beste collega's, familie en vrienden,
beste toehoorders,

In my farewell address as a full professor for more than 20 years at Eindhoven University of Technology, I would like to give a brief overview of the challenges and opportunities for building performance simulation.

It was during my undergraduate studies here at TU/e - now almost 50 years ago - that I first became interested in this technology. This continued throughout my academic career, which included research and teaching at TNO, TU/e, the University of Strathclyde in Glasgow and the Czech Technical University in Prague. At the same time I was quite active in professional organizations such as TVVL in The Netherlands, the American Society of Heating, Refrigerating and Air Conditioning Engineers, and the International Building Performance Simulation Association because I wanted to stimulate the development and use of building simulation both in academia and in practice; hence the title of this lecture.

When I was a teenager, the Netherlands switched from city gas to natural gas after the Groningen gas field was discovered. In many homes coal stoves where replaced by central heating, which meant that not only thermal comfort but also fossil fuel consumption rapidly increased. It didn't take long before the "Limits to Growth" report by the Club of Rome was published in 1972. Ever since then I have been influenced and motivated by the 1973 energy crisis, the subsequent demand for energy saving, and later – in view of climate change mitigation – the increasing need to transition to renewable energy. Over time, energy efficiency of buildings and communities has grown at TU/e from a niche area to what is now one of the main focus areas of the Eindhoven Institute for Renewable Energy Systems.

However, we should not forget that energy use is merely the means to achieve the real objective of a building; which is to protect against undesirable outside influences, and - in the case of homes and commercial buildings - to provide a comfortable and healthy indoor environment. It can be expected that due to growing awareness of the importance for health and well-being, there will be a shift from energy-related performance to indoor environmental quality performance in the not so distant future.

Other building challenges include:
- the range from tiny houses to gigantic buildings;
- the many different stakeholders – from occupant to government;
- that buildings are (mostly) one-off designed and are built by “consortia”;
- that each building is a compromise/“optimization” based on available resources and stakeholder “wishes”;
- that construction ranges from DIY to industrial;
- that buildings have a long (expected) lifetime and therefore need to be robust (e.g. for different future usage and climate changes);
- that buildings are (becoming more) complex;
- that buildings are (becoming more) interconnected and are shifting from energy consumers to prosumers.

For the building sector this implies the need to come up with 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.

So, the ultimate goal is a zero-carbon sustainable built environment in which the indoor environment is optimized for health, comfort and/or productivity. Obviously, this will need the expertise and cooperation of many different technical and non-technical disciplines. However, we also feel that computational building performance modeling and simulation can be very supportive in this.

Building Performance Modeling and Simulation

Modeling is creating a computer-based simplified representation of a real system that allows to concentrate on the essentials of a (complex) problem while leaving out details that are not relevant for the issues at hand. Simulation is using a model

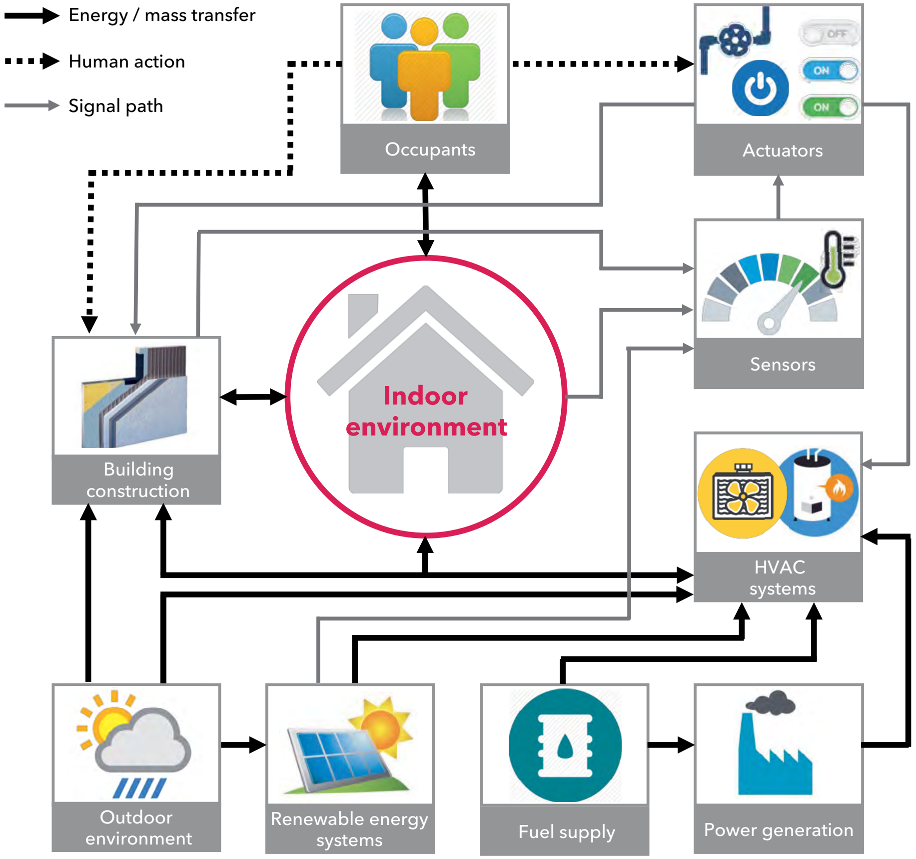


Figure 1. Dynamic interactions of (continuously changing) sub-systems in buildings [Hensen and Lamberts 2019]

to predict the behavior of a real system in the future. In our case the main objective is analysis and optimization of dynamic systems such as sketched in Figure 1.

Although very powerful, it is important to recognize that (1) simulation does not directly generate solutions or answers – its main purpose is to analyze and increase understanding, and that (2) most of the time it is not trivial to ensure that the simulation results are correct and meaningful.

Research, development and application of building performance simulation started in the 1960s. The rapid increase of related activities and publications shows that the discipline of building performance simulation is continually evolving and maturing. Whereas in the early days the main focus was on modeling and software features, attention has moved in recent decades towards improving the effectiveness of building performance simulation throughout the building life cycle stages.

Now, let's have a look at some of the application areas we have been working on. We will follow the building life-cycle from product development onwards. There is no time to explain it in detail now, but in each case new models and/or approaches had to be developed to enable co-simulation with models from different domains, or for uncertainty and sensitivity analysis, multi-objective optimization or for occupant behavior modeling.

EXPLORING IDEAS

In the **Climate Adaptive Greenhouse** project, several universities, knowledge institutes and agricultural professionals explored whether continuously adapting thermal and optical properties of a greenhouse cover, depending on the weather and crop requirements, would result in substantial energy saving and increased crop growth. This is a thought experiment because in the real world it is not yet possible to dynamically change properties such as U-value, inside and outside emissivity, photosynthetically active radiation transmittance and near-infrared transmittance. However, in simulation we can change these properties every month or every hour as we please.

The results in Figure 2 show that there is a considerable crop production increase when a generic greenhouse is optimized for a specific product such as tomatoes. Changing from static to dynamic greenhouse cover properties has little effect on crop production but would result in considerably lower gas consumption. Based on the 2015 prices for natural gas and tomatoes, it didn't look like a promising business case for the growers. However, when considering the predicted CO_2 emissions, climate adaptive greenhouse covers look very promising for carbon footprint reduction.

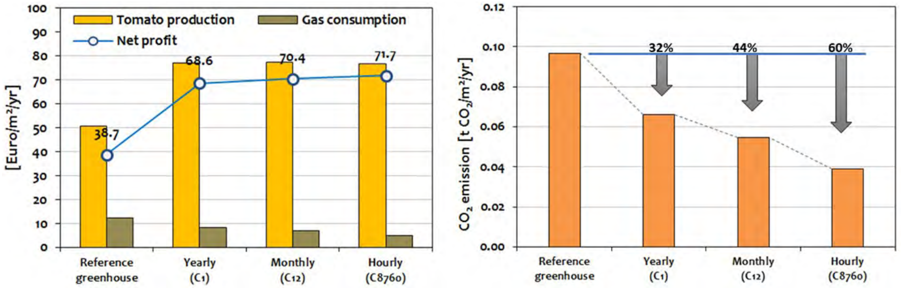


Figure 2. Predicted crop production, gas consumption and CO_2 emission for a generic reference greenhouse; one in which the optical and thermal properties are constant and optimized over the year for tomato production (C1) or where optical and thermal properties can change and are optimized per month (C12) or per hour (C8760). Costs and profit are based on 2015 prices. [Adapted from Lee et al. 2019]

PRODUCT R&D SUPPORT

Advances in material sciences open up a growing range of opportunities for new building envelope technologies. Examples include vacuum insulation, phase change materials, complex fenestration systems and facade coatings with advanced properties. Most of these concepts start off as small projects in research laboratories. Typically, academic research groups can develop such concepts from discovery up to a point with a low technology readiness level (TRL). The subsequent phases of technology transfer and commercialization into marketable products and services, however, tend not to be straightforward. As indicated in Figure 3, this has to do with the different actors and funding in the later R&D phases.

Building performance simulation can help to overcome the so-called *Valley of Death* in innovation processes by providing insights into building-integration issues in an early R&D phase.

Through iterative evaluation of multiple product variants, the integration of simulation allows for strategic decisions that acknowledge high-potential directions in the development process. What-if analyses can be performed to evaluate the robustness of a new technology in many different usage scenarios and operating conditions. Moreover, BPS can act as a virtual test bed to assess the potential of materials with properties that do not yet exist. All these analyses can be done on the basis of relevant performance indicators and, as such, the method may help create a competitive advantage by improving product performance or time-to-market in a cost-effective way.

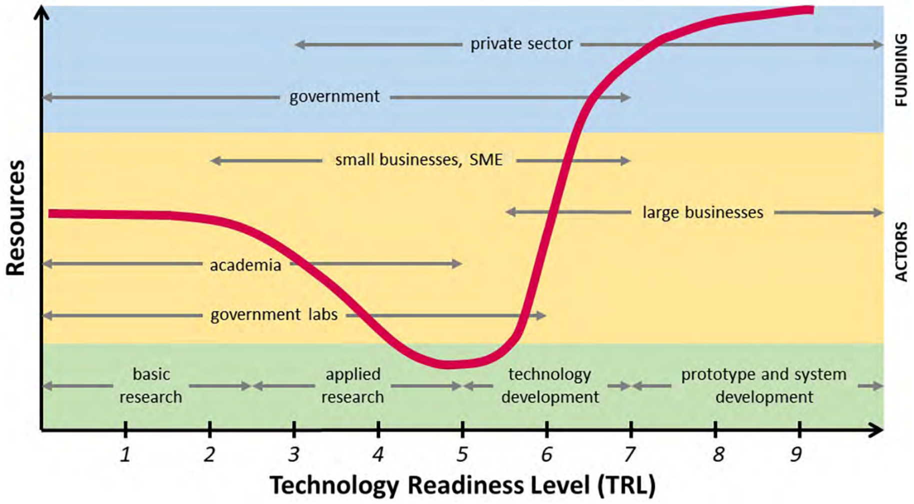


Figure 3. Availability of resources for new product development at various TRLs. The gap in the middle is sometimes referred to as "The Valley of Death". [Loonen 2018]

An example of this is **Smart Energy Glass** that has been developed by the TU/e spin-off Peer+. This technology combines liquid crystalline materials with window-integrated PV cells to create fast-switching, self-sufficient switchable glass. By regulating the amount of daylight and solar gains they transmit, absorb and reflect, these windows offer options for improving energy performance and comfort conditions.

In this case the use of simulations started during a very early phase (TRL 2-3). At the time when the technology was only available in the form of small-scale samples, we used simulations to predict whole-building performance in terms of comfort and energy saving potential under a range of operating conditions and building use scenarios (Figure 4). Based on this information, benchmarks were set and specific material-level development targets were outlined.

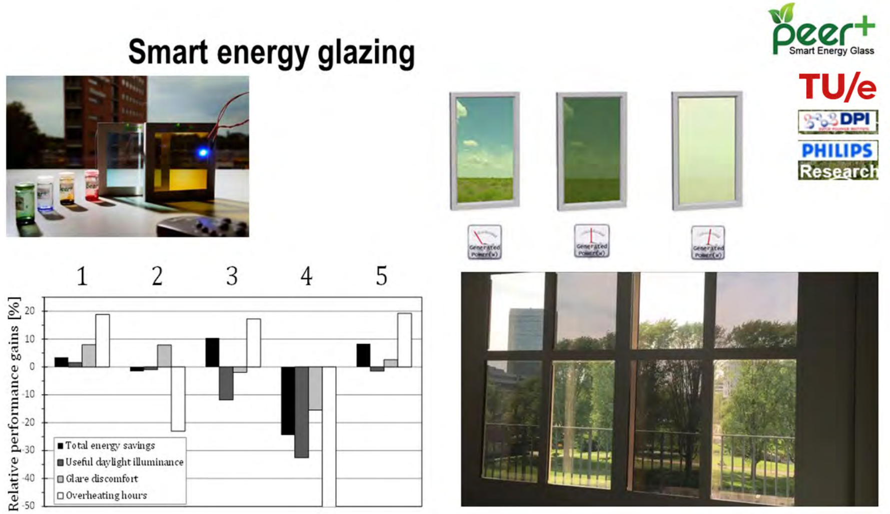


Figure 4. Smart energy glazing performance. Options 1-5 represent different control strategies. [Adapted from Loonen et al. 2014]

At a later stage, we combined BPS together with sensitivity analyses and parametric studies. These structured design space explorations helped gain information about the performance of a large number of possible product variants, without the need for many prototypes.

BUILDING DESIGN SUPPORT

Most commercial buildings are based on a one-off design, and it is not feasible to create a prototype beforehand that can be tested in reality. Quite often the designers and consulting engineers are unsure about certain (innovative) building features. In such cases, building performance simulation can be used for risk analysis and optimization of mitigation measures. Figure 5 shows some real world examples, where there was doubt about the double-skin facades; the sizing of the air-conditioning system of a historical water mill that was converted into a museum and art gallery; the draft on the platform and walkways when metro trains enter or leave the underground station; and the indoor environment and condensation risk in a tropical zoo pavilion.

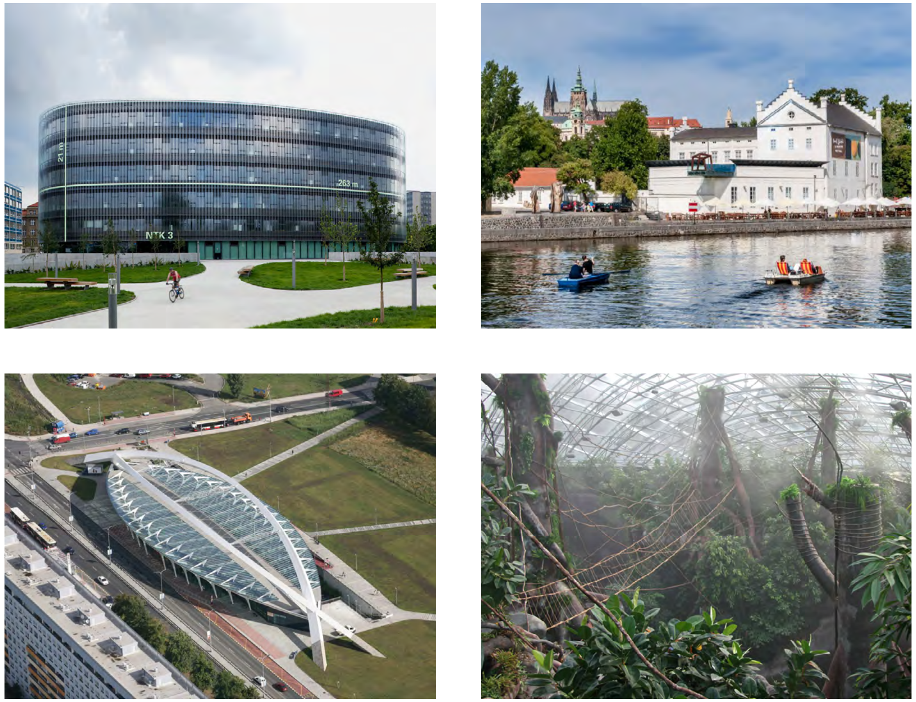


Figure 5. Examples of real buildings where simulation was used during the design for risk analysis of certain features. A = National Library of Technology, B = Museum Kampa - Sovovy mlyny, C = Strizkov metro station, and D = Indonesian jungle pavilion; all in Prague, Czech Republic.

In research we look at more general issues. For example, to investigate the potential of hybrid adaptable thermal storage concepts for reducing heating energy demand, while maintaining or improving thermal comfort in lightweight houses. This concept combines the thermophysical benefits of low and high thermal mass buildings by adapting to the most optimal thermal capacity. One way to implement this would be by placing phase change material above a ceiling that can be opened and closed on demand. Interesting applications would be in tiny houses, floating houses and so-called topping-up projects.

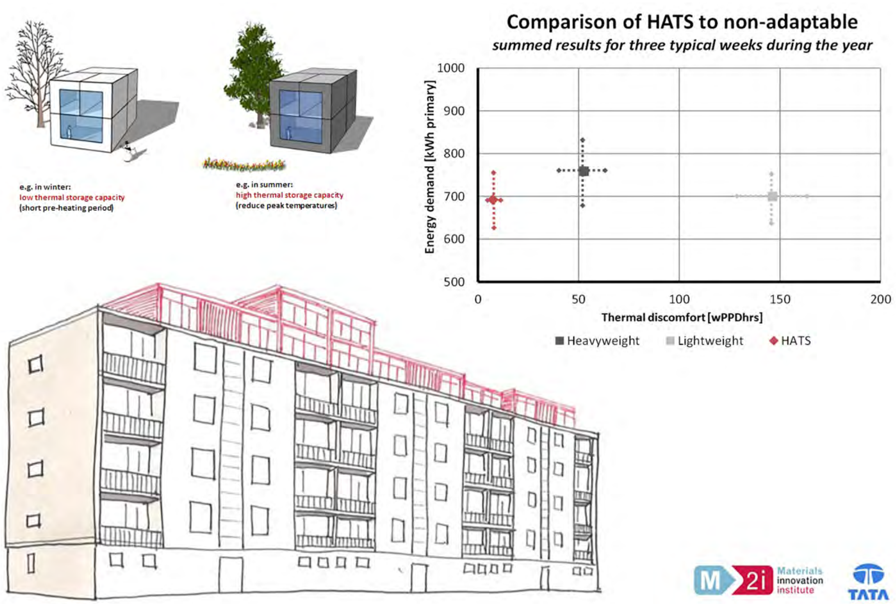


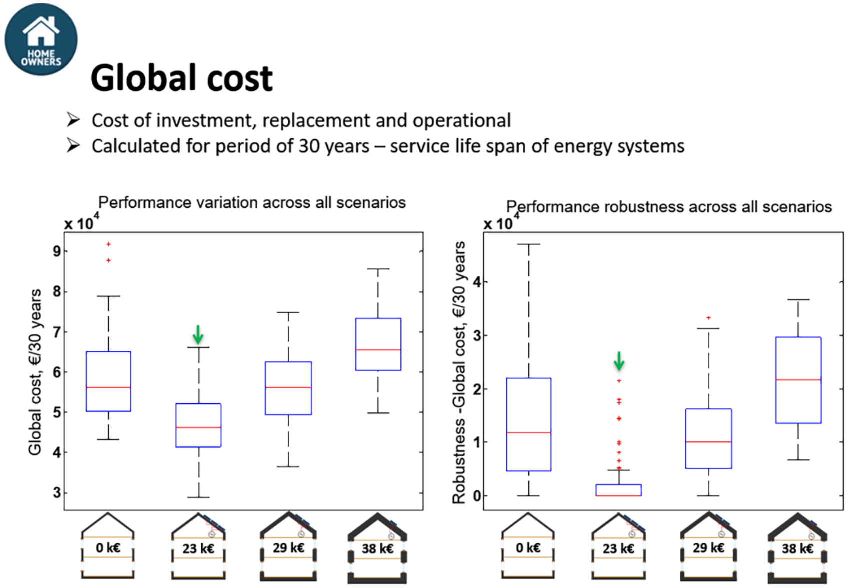
Figure 6. Hybrid adaptable thermal storage concepts for lightweight houses that can reduce both heating energy demand in winter and thermal discomfort due to overheating in summer. [Adapted from Hoes and Hensen 2016]

Another area of interest is the robust energy-efficient retrofitting of houses. Uncertainties in building operation and external factors such as occupant behavior, climate change, energy prices, policy changes etc. impact building performance, resulting in possible performance deviation during operation compared to the predicted performance in the design phase.

The probability of occurrences of these uncertainties are usually unknown and, hence, scenarios are essential to assess the performance robustness of buildings. Therefore, a non-probabilistic scenario analysis, has been developed to identify robust designs. Maximum performance regret calculated using the minimax regret method is used as the measure of performance robustness. In this approach, the preferred robust design is based on optimal performance and performance robustness.

Consider the case of a 1992 single-family home that has to be converted to net zero-energy by adding extra insulation for demand reduction and PV panels for energy generation. The investment cost will depend on the insulation level and the number of PV panels.

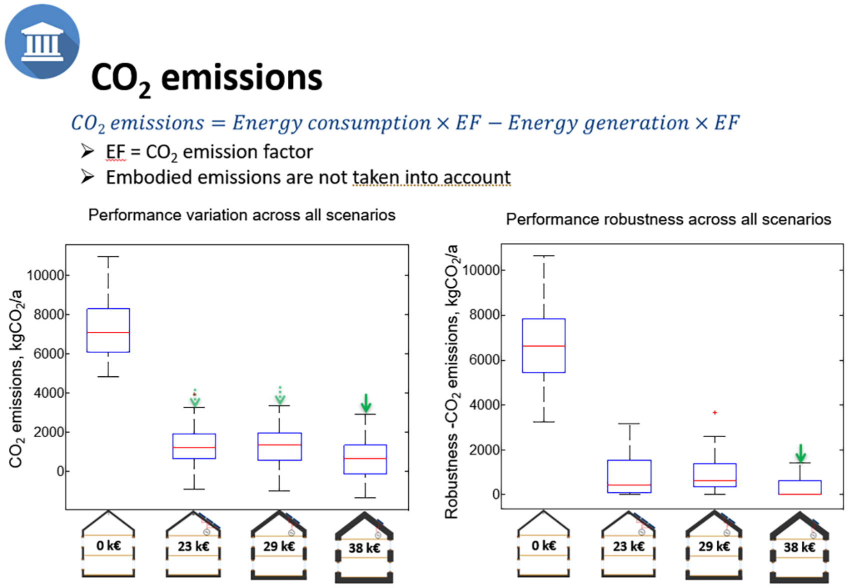
Similar to the case of the agricultural greenhouse, here it is also clear that the preferred solution depends on the viewpoint of the stakeholders. Assuming that home owners are very likely most interested in investment and operation costs, they would probably prefer the solution with not so much extra insulation but with a rather large number of PV panels. The government, however, is committed to putting CO_2 emission reduction policies in place. From the results it is clear that the solution with more insulation would be more effective in that context.



Global cost

- Cost of investment, replacement and operational
- Calculated for period of 30 years – service life span of energy systems

Figure 7. Predicted global cost for different renovation packages aiming at annual net zero-energy for a 1992 house assuming a wide range of occupant behavior and climate change scenarios. The right hand graph shows robustness in terms of regret (= performance difference between the solution considered and the best performing solution for a particular scenario). [Adapted from Kotireddy et al. 2018]



CO_2 emissions

$$CO_2\,emissions = Energy\ consumption \times EF - Energy\ generation \times EF$$

- EF = CO_2 emission factor
- Embodied emissions are not taken into account

Figure 8. Predicted CO_2 emission for different renovation packages aiming at annual net zero-energy for a 1992 house assuming a wide range of occupant behavior and climate change scenarios. The right hand graph shows robustness in terms of regret (= performance difference between the solution considered and the best performing solution for a particular scenario). [Adapted from Kotireddy et al. 2018]

BUILDING OPERATION SUPPORT

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. Work we have done in the **Genic project** is an example of this. Figure 9 illustrates the outcome which is a cyber physical system or platform that integrates computational and physical processes. It enables testing and optimization of novel control strategies and tactics without compromising the operation of the real data center.

It would be quite conceivable to develop this approach further into a digital twin. The difference is that whereas a simulation (model) predicts the “future” behavior of an (imaginary) product in an assumed world and time, a digital twin uses both the physical system and a digital copy to forecast the behavior of a real product in the real world and in real time.

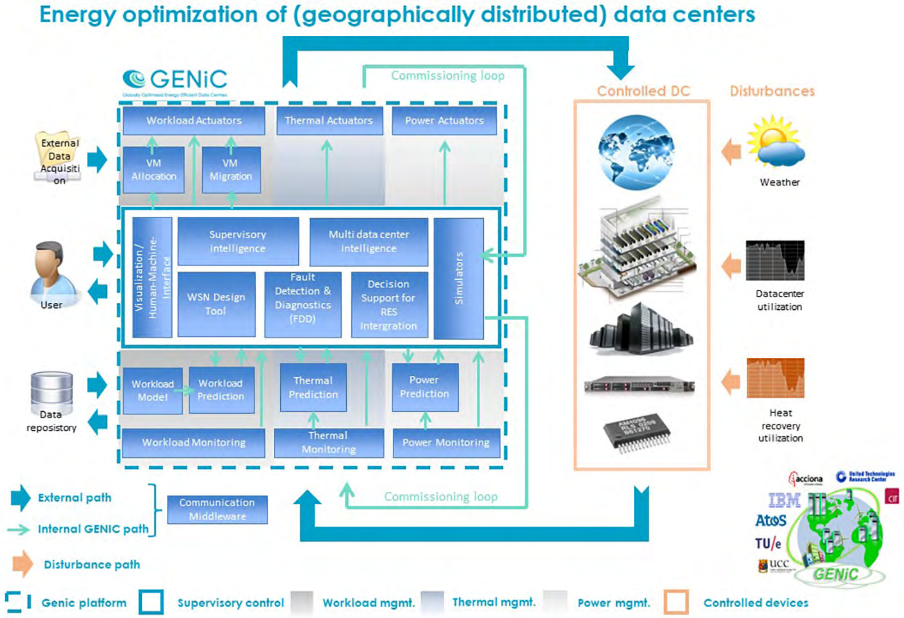


Figure 9. The GENiC architecture for integrated data center energy management [Adapted from Pesch et al. 2017]

Some reflections and viewpoints

These were just snapshots of some of the things we have been doing. In the interest of time, I haven't even touched on our ongoing research on energy flexibility in buildings, district thermal networks, mobilized heat storage and grid connected buildings. These are all important topics for the integration of renewable energy systems in the built environment. I leave it to my younger colleagues to present this at other occasions.

Now I would like to share some reflections and viewpoints with you.

DESIGN VS OPERATIONAL OPTIMIZATION

There are many differences between design and operational building energy optimization. The range in predicted energy use resulting from design choices can be many times larger than the deviations due to non-optimal building operation. The practical implications are also quite different since modifying a building after completion (e.g. changing glazing or insulation) is much more difficult than to update the building energy management system in an existing building.

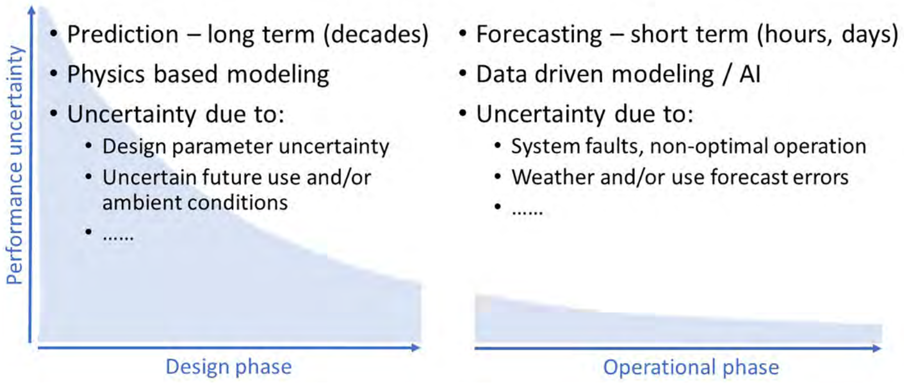


Figure 10. Main differences in performance uncertainty emanating from simulations in the design or operational phase of a building.

During design we have to consider a huge design space; a very long time horizon, highly uncertain future use and boundary conditions. As indicated earlier, in practice building simulation is typically used in design to analyze, avoid risks and to check compliance with regulations. It is rarely for optimization under uncertainty. However, this is likely to change soon because of (1) the increased awareness of the relevance (including the emergence of business models based on performance guarantees), and (2) the availability of more practicable tool chains.

There is no readily available performance data for incorporating innovative solutions and optimizing building design. Therefore, we have to use and rely on deterministic (physics-based engineering equations) rather than data driven modeling approaches.

Once the building is constructed and operating, real performance data will be available that can be used for data-driven and other artificial intelligence-based modeling and simulation approaches. The time horizon of interest is much shorter than during design (think of hours and days rather than decades). Use and boundary conditions are "known". Therefore, deviations between forecasted and real energy use are likely to be attributable to system faults or non-optimal operation. Hence, typical applications are fault detection and diagnostics, smart maintenance and control optimization.

This is already being done on individual and building portfolio level. However, it also holds great promise for management and control optimization of, for example, energy flexibility in buildings, virtual power plants and smart energy hubs that include buildings as well as electric vehicles and other energy storage and prosumer entities.

BUILDING INFORMATION MODELING

In our simulation context, building information modeling (BIM) can be seen as a promising interchange mechanism between the various tools that are used throughout the building life cycle. BIM potentially allows computational tools to manipulate the model directly, with or without human intervention.
In a typical BIM-enabled process, the data model serves as the principal means for communication between activities and professionals.

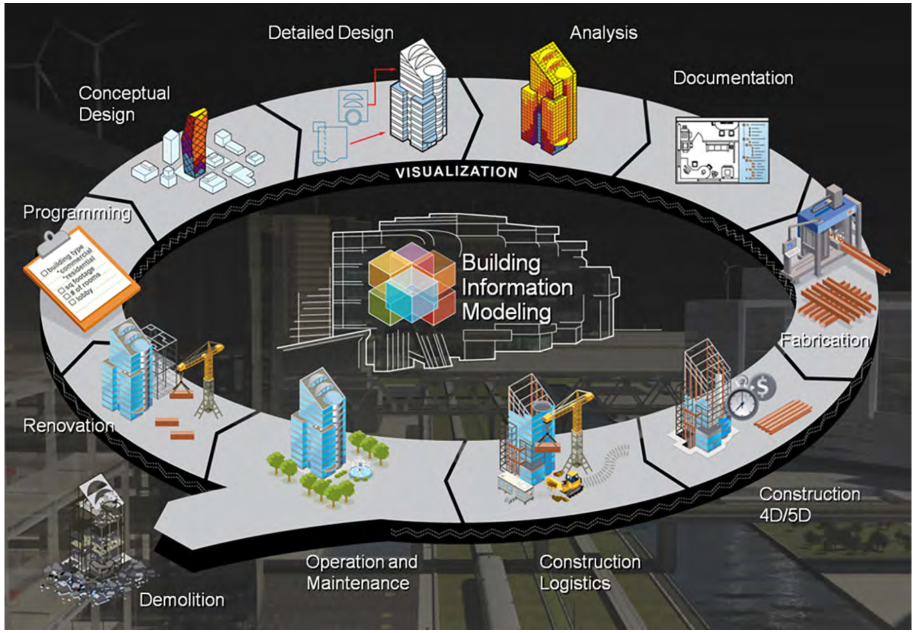


Figure 11. Building information modeling throughout the building life cycle [courtesy of Autodesk]

BIM also makes it easier to incorporate computational design approaches such as parametric modeling and generative design. While these are hugely promising for building performance optimization, they are also susceptible to the negative effects of the hype cycle of emerging technologies, that is, the peak of inflated expectations followed by the trough of disillusionment, before eventually reaching the plateau of productivity.

As has happened in the past with building performance simulation and computational fluid dynamics, it can be expected that one of the main causes of the disillusionment will be lack of trust in the results if there is insufficient quality assurance.

QUALITY ASSURANCE

What does the quality assurance of simulation-based decisions actually involve? Firstly, the quality of simulation results depends on the correctness of the model; in other words, are the predicted numbers correct? Most of the time they are not, which results in the so-called performance gap. This difference between predicted and real measured energy performance is caused by issues during the design phase (e.g. model limitations, input parameter assumptions); the construction and commissioning phase (e.g. construction flaws, differences between assumed and actual materials, components and systems); and the operation phase (e.g. systems not working properly and/or differences between assumed and actual building usage).

A lot of ongoing research aims to improve the predictions. For example, about how to consider climate change and how to take local weather phenomena (e.g. urban heat island, and wind effects in urban areas) into account.
For commercial buildings research currently focusses on commissioning and the operational optimization of building services systems.
For homes, however, actual occupant behavior is the major cause of uncertainty by far. While a lot of research has been done already, there are still ongoing concerted research efforts towards more effective and efficient occupant behavior modeling and simulation.

Energy label calculations tend to ignore these uncertainties. Labels are not meant to indicate future energy use and, therefore, should not be interpreted as such.

Since building energy simulation is now at the level where incorporation of uncertainty and sensitivity analysis is feasible, the results should always be presented with uncertainty ranges and preferably with sensitivity analysis outcomes as well.

The 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 (i.e. the results to be communicated to decision makers) can only be "assured" when it is based on quality assurance during every step of a simulation study. This begins with the relevance and accuracy of the problem formulation.

The examples I illustrated above are really based on different problems communicated by different stakeholders. Therefore, they need to be approached differently. It is not even always the best approach to use modeling and simulation – sometimes the problem can be solved by common sense or it would be better to use physical experiments.

It is crucial to start with validation, verification and testing in this initial phase and continue with it throughout the full life cycle of a simulation study. The procedures for doing this are familiar from other research fields (e.g. operations research) but they are not often used in our field. Since we have been teaching this to our students for many years now, it is hopefully only a matter of time before they become common practice.

TEACHING

Speaking about teaching, it seems rather obvious that the quality of simulation results and conclusions cannot be assured unless it is based on thorough domain knowledge. And so the main thrust in our education is to teach about building performance.

When I was a student, we only had courses on numerical methods but nothing about simulation. Nowadays, modeling and simulation are taught from the early education stages onwards. Therefore, our simulation courses and student projects can focus on specific building performance modeling and simulation skills along with knowledge about principles, assumptions, limitations, when to use and when not.

The ability to identify valid information from incorrect information is a very important skill to have. Credibility as a professional hinges on the accuracy of the information they will use. Thus learning how to assure the quality of simulation results is an overarching goal and very important, because poor quality or wrong information may have severe consequences for the built environment and human well-being.

Closing words and thanks

Challenges abound for the built environment. To tackle these, we first and foremost need intelligent people, with an appropriate background as well as smart techniques and approaches. I hope that I've been able to show that building performance simulation is one of these.

I have thoroughly enjoyed spending my professional career in this field and I have many to thank for that.

In the first place, TU/e for trusting me to develop this field and for providing an excellent environment and giving the academic freedom to pursue interesting topics together with many nice people.

I'm deeply indebted to all the academic and support staff of the Department of the Built Environment and, in particular, to my colleagues at the Building Physics and Services unit for their collegiality and for creating a wonderful working environment.

I couldn't have done what I've done without the help of all the current and former Building Performance colleagues, postdocs, graduate and undergraduate students. It has been a real pleasure and honor for me to work with you and I wish all of you the very best for the future.

Last but not least, I want to thank my family and friends for being there for me when needed. Thanks are due to my parents, who are unfortunately no longer with us; for encouraging me in my studies and laying the foundation for me to grow from.

But most of all, my heartfelt thanks and love go to Lada and my sons Michal and Daniel.

Ik heb gezegd.

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Curriculum Vitae

Prof.dr.ir. Jan Hensen was appointed as a full professor of Building Performance in the Department of the Built Environment at Eindhoven University of Technology (TU/e) on October 1, 2002.

Jan Hensen (1953) graduated from the TU/e Department of the Built Environment in 1981, after which he joined the Netherlands Organisation for Applied Scientific Research (TNO). In 1991, he obtained a doctoral degree from TU/e on the subject of building performance modeling and simulation. From 1993 to 2000, he worked in the Department of Mechanical Engineering at the University of Strathclyde in Glasgow. In 2002, he was appointed as a full professor of Building Performance at TU/e, as well as a full professor of Environmental Engineering in the Department of Mechanical Engineering, Czech Technical University, Prague. Throughout his career, his research and teaching have focused on computational modeling and simulation for optimizing the design and operation of high-performance buildings in terms of energy use and indoor environmental quality. He is a Fellow of the International Building Performance Simulation Association (IBPSA), Fellow of the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE), Fellow of the Federation of European Heating, Ventilation and Air Conditioning Associations (REHVA) and has received several other national and international scientific and professional awards.

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