

# Uncertainty propagation and sensitivity analysis techniques in building performance simulation to support conceptual building and system design

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

Struck, C. (2012). *Uncertainty propagation and sensitivity analysis techniques in building performance simulation to support conceptual building and system design*. [Phd Thesis 1 (Research TU/e / Graduation TU/e), Built Environment]. Technische Universiteit Eindhoven. <https://doi.org/10.6100/IR735575>

**DOI:**

[10.6100/IR735575](https://doi.org/10.6100/IR735575)

**Document status and date:**

Published: 01/01/2012

**Document Version:**

Accepted manuscript including changes made at the peer-review stage

**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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# **Uncertainty propagation and sensitivity analysis techniques in building performance simulation to support conceptual building and system design**

Proefschrift

ter verkrijging van graad van doctor aan de  
Technische Universiteit Eindhoven, op gezag van de  
rector magnificus, prof.dr.ir. C.J. van Duijn, voor een  
commissie aangewezen door het College voor Promoties  
in het openbaar te verdedigen op woensdag  
7 november 2012 om 16.00 uur

door

Christian Struck

geboren te Berlijn, Duitsland

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Dit proefschrift is goedgekeurd door de promotoren

prof.dr.ir. J.L.M. Hensen

en

prof.ir. P.G.S. Rutten

Copromotor

dr.ir. P.J.C.J. de Wilde

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Samenstelling promotiecommissie:

Rector Magnificus, voorzitter

prof.dr.ir. J.L.M. Hensen, *Technische Universiteit Eindhoven*, 1<sup>e</sup> promotor

prof.ir. P.G.S. Rutten, *Technische Universiteit Eindhoven*, 2<sup>e</sup> promotor

dr.ir. P.J.C.J. de Wilde, *University of Plymouth*, copromotor

prof.dr.ir.arch. S. Roels, *Katholieke Universiteit Leuven*

prof.dr.-ing. C. von Treeck, *RWTH Aachen*

prof.dr.ir. B. de Vries, *Technische Universiteit Eindhoven*

ir. P. Stoelinga, *Deerns Rijswijk*

This research project was generously funded and supported by:



A catalogue record is available from the Eindhoven University of Technology Library.

ISBN 978-90-386-3242-1

NUR 955

Cover design by Reflector.ch and adapted by Paul Verspaget. Printed by the Eindhoven University Press, Eindhoven, The Netherlands. Published as issue 173 in de Bouwstenen series of the Faculty of the Built Environment of the Eindhoven University of Technology.

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## Acknowledgement

Now that I know...

... my limits physically, psychologically and emotionally, and the extent of the support needed, I would not do it again; that said, considering the experience, the friends made, and the knowledge gained, it was worth it.

My gratitude goes first to my two promotors, Jan L. Hensen and Paul Rutten, for the introduction to the international scientific community and for their guidance throughout the project. Jan, I thank you for sharing your enthusiasm and commitment to continually advance building performance simulation. Paul, many thanks for sharing your valuable insights into the design process and alternative design approaches.

I especially thank my Supervisor, Pieter de Wilde, for his continuous scientific support and encouragement throughout the project, first between Delft and Eindhoven, then between Plymouth and Eindhoven and finally between Plymouth and Lucerne. Your input to the final draft of the thesis, during my three-week stay with you in Plymouth in February 2012, proved invaluable.

Furthermore, I thank the two companies for co-founding the research project; VABI BV and Deerns BV. Dear Aad, Wim, Luc and Paul, I am grateful for your input to the project through our individual meetings, cooperative publications and feedback during my monthly PhD progress presentations.

I need to thank Urs-Peter Menti, the head of the Centre for Integrated Building Technology at the Lucerne University of Applied Science and Arts, for understanding and supporting me during the final steps.

However, without the friendship and discussions within our research-group, with visiting researchers and with my students, the process would have been much less pleasant. I have to thank my co-scientists: Monica Melhado, Marija Trcka, Daniel Costola, Mohammad Mirsadeghi, Wiebe Zoon, Azzedine Yahiaoui, Gülsu Ulukavak Harputlugil; visiting researchers: Petr Kotek, Christoph van Treeck, Michael Emmerich, Martin Bartak and Milos Lain; Students: Janneke Evers and Jelle Roelofs. I am especially indebted to Christina Hopfe for her companionship, friendship and support from start to finish. I am glad I met you!

I also have to thank the consulted experts in academia and design practice for their time and insight. My thanks go to: David Gilpin, Timucin Harputlugil, Koos Mast, Elphie Nelissen, Joop Paul, Emiele Quanjel, Ed Rooijackers, Hans Ruchti, Paul Stoelinga, Wim Plokker, Luc Southout, Aad Wijsmann, Ant Wilson, Mike Holmes, Jaap Wiedenhoff, Neil Billett and Wim Zeiler.

I want to thank Ineke, Jaap, Ylan and Robert for supporting both of us, my wife Cath and me. I am greatly indebted to my parents Karin and Karl-Ernst and my brother Matthias, for sticking with me throughout the ordeal. Between them, they provided me with endless emotional, practical and financial support, which got me through tears and fears. I thank my children Hidde and Feya for their unconditional love and undisturbed belief in their dad expressed through warm hugs and tender kisses.

Special thanks are reserved for my wife who provided me with a net when the floor collapsed beneath my feet; for feeding me love and assurance; for providing believe when I lost it. My dear Cath, I would not have been able to complete the work without you!

---

## ***“On the use of dynamic energy simulation tools***

*We constantly underestimate the impact on society of the field of building performance simulation. Let's take some pride in what we do!*

*Most of the wealth of developed nations lies in the value of buildings. That value is now starting to be related to the actual performance of those buildings. (Funny this hasn't happened before.) An example of this is that venture capitalists are starting to show interest in the validation status of building performance software. They want to know if they can trust the numbers quoted by someone selling a property. This would hardly have happened a few years back.*

*Suppose an engineering-proficient company, perhaps like Toyota, was challenged with the task of developing a high performance building. Do you think they would look for the latest ISO standardized monthly hand calculation method for its optimization? No, they would look for the best possible engineering tools available for describing and experimenting with dynamical virtual models of buildings. (Actually, they might not do so well first because they would probably underestimate the pure technical challenges involved).*

*Even a big ship, such as the AEC industry, will turn eventually in response to the challenges ahead. At that stage, real knowledge and engineering skills are likely to be more important than committee designed hand calculation methods.”*

Per Sahlin (2012); email to the bldg-sim mailing list from the 2<sup>nd</sup> of February.



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## Summary

Due to advances in computing and modeling, the Architecture Engineering and Construction (AEC) industry has arrived at an era of digital empiricism. Computational simulation tools are widely used across many engineering disciplines for design, evaluation and analysis. Experts in the field agree that design decisions taken during the early design stages have a significant impact on the real performance of the building. Nevertheless, building performance simulation is still hardly used during conceptual design.

The European Commission has targeted a 20% reduction of CO<sub>2</sub> emissions, a 20% increase of energy efficiency and a 20% increase in the use of renewable energy by 2020. These ambitious aims have resulted in the recasting of the Energy for Buildings Directive, demanding nearly-zero-net-energy-buildings for new buildings and major refurbishments by 2020. The formulated aim requires for the first time an integrated design of the building's demand and supply systems.

The current research was triggered by the above observation. It uses semi-structured interviews and critical reviews of literature and software to establish the reasons that prevent Heating, Ventilation and Air Conditioning (HVAC) consultants from adopting Building Performance Simulation (BPS) tools and to identify the needs of practitioners during the conceptual design stage. In response to the identified needs, a rapid iterative development process is deployed to produce a prototypical software tool. Finally, the tool is heuristically tested on expert users to evaluate its capability to support the conceptual design process. The results obtained from interviews and reviews highlight that HVAC consultants work with an increasing number of design alternatives to prevent dysfunctional buildings. The complexity of design problems is increasing on the one hand due to the need for an early integration of engineering discipline's and on the other hand due to the challenges in meeting the even more stringent requirements of new buildings.

Furthermore, design teams run the risk of only identifying suboptimal solutions for the design problem when they limit themselves too early to a small number of design alternatives. The use of simulation tools helps facilitate a quick turnaround of performance evaluations for a great number of design alternatives early in the design process. By doing so, performance simulation tools have the potential to supplement design experience and support decision making. However, simulation tools are perceived by many as too detailed to be readily used for conceptual design support. Research findings suggest that tools for the early design stages are required to enable parametric studies and to provide facilities to explore the relationships between potential design decisions and performance aspects.

Tools need to be able to dynamically scale the resolution of their interfaces to fit the different levels of information density characteristic of the different design stages. In addition, they need to be flexible enough to facilitate expansion of the system representations with innovative design concepts as the design progresses.

Due to the need for parametric studies and the exploration of the relationships between potential design decision and performance aspects, this research explores the extension and application of BPS tools with techniques for uncertainty propagation and sensitivity analysis for conceptual design support. This endeavor requires (1) the evaluation and selection of an extension strategy, (2) the determination of the format and availability of input to techniques for uncertainty propagation and sensitivity analysis, as well as (3) developing knowledge regarding the extent and content of the design option space.

To avoid the need to modify the source code of BPS tools, an external strategy is applied that embeds an existing simulation engine into a shell with extra features for statistical pre and post-processing by Latin Hypercube sampling and regression based sensitivity analysis. With regards to the model resolution, results suggest that it is more beneficial to use detailed models with adaptive interfaces rather than simpler tools. The advantages are twofold. Firstly, the BPS tool can use an existing validated simulation model - rather than a specifically developed abstract model with limited applicability. Secondly, the model is able to provide consistent feedback throughout the lifetime of the building.

Within the iterative process, the conceptual design stage has some distinctive tasks, such as to explore the option space and to generate and evaluate design concepts. The option space is multi-dimensional, due to its multi-disciplinary set-up and wide-ranging interests of the participating practitioners. An empirical study as part of the research demonstrates the presence of at least two attributes, four subsystem categories and four relationships. Depending on the experience of the practicing designer, components, attributes and relationships are used to a very different extent. While experienced HVAC consultants seem to work mainly with relationships when compiling a design concept, novice designers prefer to work with components.

The sampling based analysis strategy requires knowledge about the uncertainty of the parametric model input in the form of probability distribution functions. On the basis of a survey on internal gains for offices, this thesis concludes that current design guidelines provide useful data in a suitable format. Measurements conducted in an office building in Amsterdam confirm the trend towards decreasing equipment gains and the proportional increase of lighting gains. However, in the absence of data to derive a probability density function, this research suggests the definition of “explanatory” scenarios. It is common practice to use “normative” scenarios as input in building performance studies aiming to prove compliance with building regulations. The use of “exploratory” scenarios is less common. Scenario based load profiles have to meet three characteristics. They have to be: (1) locally representative; (2) up-to date and (3) need to match workplace culture.

As part of this thesis explanatory data sets were developed representing climate change scenarios for The Netherlands. The exploratory scenarios facilitate the robustness assessment of the future performance of design alternatives. Tests with the Dutch data sets confirm that neither the current reference data nor the projected reference data provide valid results to predict uncertainty ranges for the peak cooling load as a potential robustness indicator. A simulation based comparative robustness assessment of three HVAC concepts over 15 and 30 years is reported. The results indicate a robust future performance for the floor-cooling based design alternative with respect to thermal comfort and cooling energy demand.

The software prototype shows that detailed simulation tools with features for uncertainty propagation and sensitivity analysis provide the facilities to explore consequences of potential design decisions on performance aspects. In addition, they enable parametric studies and create the possibility to quantify parameter interactions and their collective impact on the performance aspect.

Heuristic usability evaluation of the software prototype confirms the value to design practice. 85% of approached HVAC consultants state that the uncertainty of performance aspects is an important parameter to support conceptual design. More importantly, 80% of the practitioners consider the prototype to have great potential to reduce the number of necessary design iterations.

This thesis concludes that simulation tools that quantitatively address uncertainties and sensitivities related to conceptual building design generate value by (1) providing an indication of the accuracy of the performance predictions; (2) allowing the identification of parameters and systems to which performance metrics react sensitively and in-sensitively, respectively; and (3) enabling a robustness assessment of design alternatives.

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# 1

## Introduction

Mankind faces a number of great challenges on a global scale, such as a growing world population, diminishing fossil resources, climate change and an aging society. The recognition of the need for change to deal with these challenges led to the formulation of the strategy for sustainable development in the Brundtland report (WCED, 1987). The report defines sustainable development as:

*“...development that meets the needs of the present without compromising the needs of the future generations to meet their own needs.”*

The Brundtland report derives the following seven objectives for environment and development policies from the concept of sustainable development:

- (1) reviving growth;
- (2) changing the quality of growth;
- (3) meeting essential needs for job, food, energy, water and sanitation;
- (4) ensuring a sustainable level of population;
- (5) conserving and enhancing the resource base;
- (6) reorienting technology and managing risk;
- (7) merging environment and economic decision making.

A number of international organizations, such as the International Monetary Fund (IMF), United Nations Environment Programme (UNEP) and International Energy Agency (IEA), have adapted their foci in accordance with the strategy of sustainable development.

The IEA for example addressed the contribution of buildings to the above named great challenges by establishing a multilateral technology initiative on Energy Conservation in Buildings and Community Systems. The aim of the initiative is to improve the energy efficiency in buildings as the building sector is accountable for up to 40% of the energy use worldwide. This is achieved through:

- energy use impact analysis;
- envelope optimization;
- advanced planning;

- enhanced use of daylight;
- computational performance diagnosis;
- improving the availability and use of design tools.

In response to the demand for a more sustainable building stock, the European Parliament's Industry Committee (ITRE) declared that from 2019 all newly constructed buildings must produce as much energy as they consume on-site (ECEEE, 2009). Minimum percentages of existing buildings achieving the "zero net energy" standard by 2015 and 2020 respectively are to be defined by the member states of the European Union (EU).

To achieve the goal the World Business Council for Sustainable Development (WBCSD, 2009) recommends the following measures:

- use subsidies and price signals to incentivize energy-efficiency investment;
- develop and use advanced technology to enable energy-saving behaviors;
- develop workforce capacity for energy saving;
- mobilize for an energy aware culture;
- strengthen the building codes and labeling for increased transparency; and
- encourage integrated design approaches and innovations.

The latter two points are of particular interest here as they relate to the design development phase. A shift from prescriptive to performance based design can be observed. Prescriptive designs make use of specifications, for example, technologies or material properties. For a performance based design the means are open for negotiation as long as the required performance is achieved. Performance based design enables the realization of architecturally and technologically advanced buildings.

To develop complex architectural and technological systems their performance must be quantified and evaluated during the design process. Paul argues in his inaugural speech (2007) that this is the era of "digital empiricism". The computational methods applied, such as the finite element method, allow situations to be tackled for which analytical solutions are not available.

Performance simulations support the design process by predicting how building structure and indoor environment respond to dynamic variations of different load types. However, application is in most cases limited to the late design stages (Clarke, 2001, Malkawi and Augenbroe, 2004).

It is important to note that building projects, particularly large ones, rarely meet the required design targets, such as investment costs and energy use. Bästlein (2002) argues that complex projects would benefit from employing techniques to facilitate a structured functional and financial risk management.

However, the management of risk requires knowledge of the origin and distribution of the underlying uncertainties and their complementary consequences on performance.

### **1.1 Problem statement**

Building performance simulation uses computer-based models to predict the performance of buildings and systems. Nowadays, it is used in the design, operation and management of a building. Different models are in use for a multitude of applications, such as energy and comfort predictions, air flow and contaminant distribution. This thesis focuses on computer-based models for energy and comfort predictions.

Even though BPS is now used in building design projects, its use is still limited. Although a large number of building simulation tools are available (Crawley et al., 2008, US Department of Energy, 2010) their application is in many cases limited to the final design stages (Clarke, 2001, Malkawi and Augenbroe, 2004). Presently, the main uses are to check for code compliance, to calculate thermal loads and to size heating and air-conditioning systems. In an increasing number of cases, this is complemented by high-resolution modeling of light and airflow for visualization purposes.

The use of building performance simulation can be extended if the community succeeds in bridging the gap between the anticipated and real user in terms of expectations, background knowledge, skills, and available resources (Hensen, 2004).

Bleil de Souza (2012) differentiates between the tool user and the building designer (architect) and identifies paradigms which seem “incommensurable”. She suggests considering tools as environments to experiment with the concepts of building physics as “craftsmen”. Extending this line of thought, the aim of experimenting is to conduct a number of impact assessments which allow project specific design guidelines to be derived both prior and during design.

The state of the art building performance tools that are used in design practice are in most cases based on simulation kernels developed in the 1970s, such as ESP-r, Apache or DOE. Their structure is either monolithic or modular. Examples of tools with monolithic structure are ESP-r and TAS. Tools with modular structure are IDA ICE and TRNSYS. These tools require expert skills to generate the required output to derive the performance data.

Although it is common knowledge that the impact of the design decisions is greatest in earlier design stages, building performance simulation is rarely used to support early design stage tasks such as concept generation and evaluation. This statement is supported by a number of previous studies (Hopfe et al., 2005, Lam et al., 2004b, Mahdavi et al., 2003). However, one needs to differentiate between studies which draw conclusions by reviewing the design and construction process of real buildings (Wilde, 2004) and studies which quantify the feedback of practitioners in interviews and questionnaires (Attia et al., 2011).

The review of real building designs provides insight which is not biased by the perspective of practitioners as to the definition of design stages and categorization of tools. Alternatively, the strength of quantifying practitioners' feedback is in identifying the likes, dislikes and projected future use of computational support tools.

Ideally, evidence regarding the current use of tools should be provided from both the perspectives of process and practitioners, but this dual perspective is rarely available. As the focus here is on supporting HVAC consultants, the lack of current work on the relationship between tool adoption and design process is omitted. During the early phases in the design process, decisions have to be made with limited resources and on the basis of limited knowledge. The decisions have major consequences during the remainder of the building systems life cycle (Blanchard and Fabrycky, 2006).

Whilst the confidence in performance measurements is indicated by providing the measurement error, simulation results are in most cases presented as point estimates. There is typically a lack of information about the accuracy of the model predictions and the impact of the design parameters on the performance indicator. One approach to enable the earlier use of BPS is to extend its capabilities. The subject addressed here is the uncertainty quantification and sensitivity analysis of the building performance due to uncertain model input.

### **1.2 Hypothesis**

The hypothesis governing this work is: "Building performance simulation tools, extended with techniques for uncertainty propagation and sensitivity analysis, have an increased potential to support conceptual building design".

### **1.3 Aims and objectives**

The aim of the thesis is to contribute to increasing use and improving usability of building performance simulation tools during the early design phase of a building. This aim is facilitated by enabling the innovative application of building performance simulation for the generation and selection of design alternatives. The approach chosen is to first research the current needs and requirements of the architecture engineering and construction (AEC) industry and then develop innovative solutions based on existing approaches. This research aims to provide tools for HVAC consultants that will allow them to take a pro-active role in the design process. The five objectives are formulated below.

- The first objective is to establish the requirements for BPS-tools to be used in the early design phases.
- The second objective is to identify and evaluate means to facilitate uncertainty propagation and sensitivity analysis to support practitioners in generating and evaluating design alternatives.

- The third objective is to assess the availability, feasibility and validity of data to serve as input for a simulation tool extended with the capability to perform uncertainty and sensitivity analysis.
- The fourth objective is to explore the characteristics of the option space which designers use and to apply the proposed tool extension to a realistic design problem.
- The fifth objective is to test the usability of the prototype in design practice.

The main results of the work are (1) strategic methodological knowledge and practical implementation experience regarding building performance simulation for conceptual design; (2) a case study based prototype simulation environment for uncertainty propagation and sensitivity analysis; (3) guiding principles for the use of the prototype for the generation and evaluation of design alternatives.

#### **1.4 Research methodology**

The research methods used are briefly described below in the order in which they were used in the research.

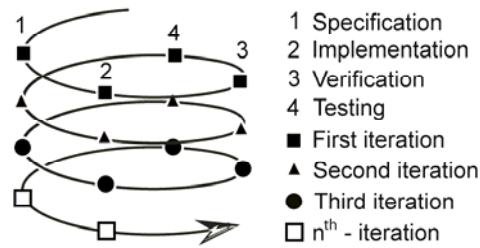
*Literature review* was conducted to gain an overview of the state of the art of BPS tools and to learn about the application of reported techniques and methods. Subjects that have been extensively reviewed are: performance simulation tools, methods and applications for uncertainty propagation and sensitivity analysis, system theory and performance based design.

*Interviews* were conducted with internationally recognized practitioners. This was to learn about the design development tasks in practicing building and services engineering and the requirements for tools to successfully support design.

*Observations* were conducted to monitor and record the design activities of students in design studios. The aim was to obtain empirical data about the elements used to compile design alternatives.

*Iterative software* development was conducted to develop and evaluate prototype software applications to conduct numerical simulations for performance predictions of representative case studies. The process consists of four steps per iteration: specification, implementation, verification and testing. It is visualized in Figure 1.1.

The specification describes the required functionality of the prototype. The implementation allows the functions to be executed in a working computational environment. Verification ensures that the prototype subroutines work as specified. Testing relates the prototype to design practice. It allows a quantification of its applicability from the user's perspective.



**Figure 1.1 Iterative prototyping**

### **1.5 Thesis outline**

Each following chapter is organized as follows: introduction, literature review, methodology, results and summary.

Chapter 2 reports on the literature survey and interviews with design practitioners. Together, these measures were taken to ascertain the state of the art in the application of building performance simulation tools for conceptual design, to identify practitioner's needs in conceptual design and to derive requirements for simulation tools.

Theory relating to uncertainty propagation and sensitivity analysis is set out in chapter 3. A number of methods are then discussed, which show the potential to support the design process by supporting the generation and evaluation of design alternatives. Furthermore, the selection of a simulation tool as a basis for the prototype development is justified by results of a literature survey and comparative simulation studies. Finally, a prototype is developed and verified. An approach is formulated to facilitate uncertainty propagation and sensitivity analysis as an extension to state of the art tools.

Chapter 4 reviews the representation and investigates the impact of occupancy pattern and climate variations in building performance simulation tools. Of particular interest is the implementation of scenario based parameter uncertainties.

The elements used for the synthesis of integrated building systems are the subject of chapter 5. First, the design process and system theory is reviewed. Then, collected empirical evidence is presented on the type and extent of system elements used to compile design concepts in practice. Finally, an application study visualizes the use of the developed prototype on a representative design.

In chapter 6 the usability of the developed computational prototype in design practice is investigated. First an overview of usability engineering techniques is provided. Thereafter, qualitative and quantitative user feedback originating from the iterative prototype developing process is presented and discussed.

Chapter 7 summarizes the research and presents the conclusions, as well as identifying open research questions.

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# 2

## Performance based design evaluation

This chapter reports the state of the art in building performance evaluation related research and practice. First, the shift from prescriptive to performance based design requirements is explored, followed by a review of efforts to facilitate the integration of design and evaluation. Thereafter, the use of tools for performance evaluation in practice is documented by providing results from interviews and a software review. The chapter concludes with a set of requirements for the development of future performance simulation tools to support the conceptual design stage.

The design of complex, integrated buildings is a dynamic and iterative process. A design is evaluated based on how it complies with set requirements. Those requirements can be prescriptive or performance-based. Other terms used for performance-based requirements are functional or objective-based requirements. Performance based evaluation criteria are, for example, tenability limits, escape time, structural loads or energy loads (Meacham, 2010).

The move away from prescriptive specifications towards functional requirements in building regulations began more than 30 years ago (Visscher and Meijer, 2006). Prescriptive specifications represent in many cases social needs or lessons learned from fatal situations. Performance based approaches aim to evaluate the building, system and component performance in the context of its use (Bukowski, 2003). In comparison to performance based requirements, prescriptive requirements are argued to have the inherent potential to hinder change and innovation as they prescribe solutions, e.g., in the form of technologies or material properties (Loomans and Bluysen, 2005).

Organizations aiming to advance performance based building include the CIB through its Task Group 11 (CIB TG11, 1997), the IRCC (Meacham et al., 2005) and the European Union through the PeBBu thematic network within the 5<sup>th</sup> Framework programme, 2001-2005 (Foliente et al., 2005). Related issues as diverse as the impact of performance based building on educational curricula (Loftness et al., 2005), quantification methods (Augenbroe and Park, 2005) and the property market (Lützkendorf and Speer, 2005) are addressed by research groups around the globe.

The PeBBu thematic network (Lee and Barrett, 2003) was motivated by the need to change the focus from specifying building and system components as input to the design and construction process towards the user requirements as process output. Lee and Barrett (2003) give the following definition for performance based building:

*“Performance-based building considers the performance requirements throughout the design life of the building and its components, in terms that both the owner and the user of the building understand, and which can be objectively verified to ascertain that requirements have been met. The requirements are concerned with what a building or building component is required to do and not with prescribing how it is to be constructed.”*

The freedom for the development of innovative design concepts is restricted by a number of fixed frontiers such as the design brief and local building regulations. The design brief can in its most stringent form prescribe design solutions (Ulukavak Harputlugil et al., 2006) whilst the authorities demand compliance with building regulations. There are growing calls in the literature for the formulation and harmonization of performance based regulations throughout Europe (Sheridan et al., 2003, Visscher and Meijer, 2006). Visscher and Meijer conclude that the severe differences in building regulations prior 2006 can be overcome by the European Performance in Buildings Directive (EPBD). The objective for adopting performance-based regulations are (Almeida et al., 2010):

- to reduce barriers to trade and increase innovation,
- to reduce regulation complexity and clarify its intent, and
- to allow more functional buildings at lower costs without sacrificing safety.

Examples of European performance based regulations are the Building regulations Part L “Conservation of Fuel and Power” in Great Britain and the “Energieeinsparverordnung” 2009 in Germany.

To stimulate clients to embrace energy and material conservation, rating-schemes are used widely. A large number of rating-schemes are available with different scope and for different phases of the building’s life cycle (Struck et al., 2004, Gowri, 2004, Fowler and Rauch, 2006, Vreenegoor et al., 2009).

Rating-schemes such as LEED (U.S. Green Building Council, 2009), BREEAM (Baldwin et al., 1998), Minergie (Minergie Agentur Bau, 2009) and DGNB (DGNB, 2009) are voluntary rating-schemes which award labels certifying a degree of building performance following the design and construction phase. The aim of the rating is to provide transparency and subsequently increase the monetary value of the rated building by showcasing its performance (Center for Corporate Responsibility and Sustainability, 2008).

For design, LEED and BREEAM claim to assess the overall environmental impact. Other schemes such as Minergie are limited to the energy demand for space, heating, cooling, ventilation and the provision of domestic hot water. Building performance evaluation during design is in many cases conducted by comparing the performance of the design proposal against a notional design (Department of Energy and Climate Change (DECC), 2009).

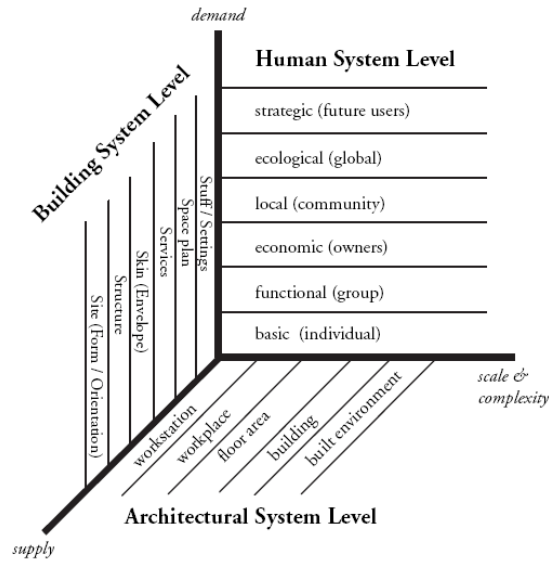


Post-occupancy evaluation frequently shows that buildings do not meet the imposed performance requirements (Crawley et al., 2009, Mills, 2009). This fact indicates that current regulations and rating-schemes cannot guarantee that the required performance is met in operation. One approach to overcome the problem is a continuous performance evaluation from design to operation. Seminal publications in the field are Preiser and Vischer (2005) and Mallory-Hill et al. (2012). To already investigate compliance with performance requirements during the design phase, it is necessary to quantify relevant performance metrics through the use of simulation tools. Almeida (2010) states that the tools should enable a statement about the reliability with which a certain level of performance can be achieved.

### **2.1 Performance evaluation**

Performance evaluation in the built environment can be conducted at different levels of abstraction and for a range of requirements. A scientific frame for performance evaluation in the built environment is provided by the field of human ecology. This human centered research field studies the interaction of humans with their natural, social and built environment (Borden, 2008). Mahdavi (1998, 2011) relates the scientific framework to building performance evaluation and differentiates two aspects: interactivity by exchanging matter and energy, and information. He states that performance simulation is typically used for predictions of the energy relevant features of the relationship between humans and the built environment.

Mallory-Hill (2004) structures the relationship in a three-dimensional “building performance evaluation domain model”. The model consists of three levels: human system level, building system level and architectural system level. Each of the levels is subdivided into a number of sublevels such as site, structure, skin, services, space, plan and stuff, see Figure 2.1.



**Figure 2.1 Building evaluation domain model (Mallory-Hill, 2004)**

Further to setting the domain, the evaluation of a design's performance requires the definition of performance requirements. For this thesis performance requirements reflect the client's expectation of the building's final performance. To quantify the building performance during the evolving design process, stated requirements need to be converted into performance indicators and metrics.

A performance indicator is thereby defined as an objectively quantifiable performance measure describing the building performance to support dialogues between stakeholders in the design process. It is an agreed upon measure to assess the achievement or failure of an integrated building system to fulfill the values of the stakeholders (Pati et al., 2006). Pati et al. (2006) differentiate between hard and soft indicators. Hard indicators originate from normative models in biophysics and physiology whereas soft indicators originate from empiricist models of environment-behavior studies. Performance indicators can be aggregates of multiple performance metrics.

A performance metric is a quantity that has three distinct characteristics, it is: (1) measurable; (2) has a clear definition including boundaries and (3) indicates progress towards a set performance goal (Deru and Torcellini, 2005).

### 2.1.1 Tools for performance evaluation

When considering computational support for performance evaluation one needs to distinguish between the design and the operational phase of buildings. Whilst the performance can be evaluated by comparing measured data to the design specification, this is not possible during the design phase.

The challenge during operation lies in handling, visualizing and mining the dynamic performance data. The development of tools addressing the issue have been reported by, e.g. Hitchcock (2002), Morbitzer (2003) and Blair et al.(2008).

Clarke (2001) explains that simulation tools developed to be used during design have evolved over four generations. The past three generation's resulted in tools that use numerical methods and provide partial integration of building aspects, e.g. comfort, energy and transportation. The current tool generation was expected to be equipped with knowledge-based user interfaces and be integrated with more aspects related to buildings, e.g. vertical and horizontal transportation as well as evacuation. Furthermore, the generation to come is expected to better fit reality and be easier to use.

Simondetti's (2008) view differs from Clarke's. Whilst Clarke suggests that future tools will be fully integrated and easy to use, Simondetti concludes from interviews with 22 international "thought leaders" (PhD candidates to industry board members) that the designer's toolkit 2020 will consist of multiple specialized software tools operated on demand. The individual tool is anticipated to represent one of many components in a collaborative web-based network.

Augenbroe recognizes in Malkawi and Augenbroe (2004) a shift away from efforts to embed "designer friendly tools" into design environments towards using services from remote domain experts, due to their instant availability via the world-wide-web. Following this line of thought, he states that the challenge will then lie in facilitating the communication between the experts and the design team members.

There are a great number of tools that claim to support the evaluation of a building design. The Building Energy Software Tools Directory (U.S. Department of Energy, 2012) lists 405 tools for the evaluation of energy efficiency, renewable energy and sustainability in buildings. There are a number of different ways to look at simulation tools. Common perspectives focus on *global purpose* which distinguishes between modeling, design and analysis; the *degree of model resolution* differentiating abstract to detailed tools, and the *evaluation objective* which discerns single objective and integrated tools.

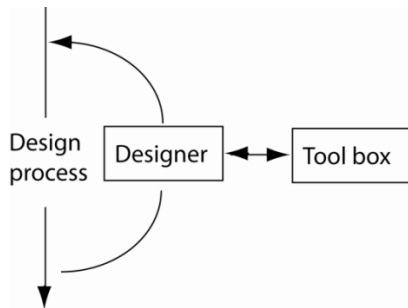
The perspective that is relevant for the current work is the global purpose, namely the tool's capacity to support the conceptual design stage by providing a basis to evaluate the performance of design alternatives.

### **2.1.2 Integration of evaluation and design**

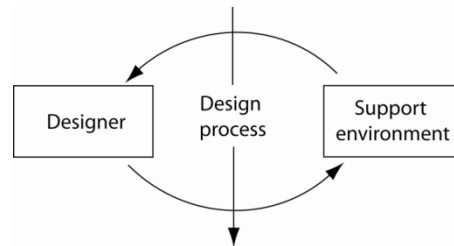
Past research efforts focused on two main areas related to the integration of performance evaluation to design: (1) data model integration for the provision and exchange of product data, and (2) design and analysis of integration environments to continuously support iterative design development.

To benefit from simulation tools during the design process Clarke (2001) argues for the application of computer-supported design environments, see Figure 2.3.

Thereby, the disadvantages of the tool-box approach (see Figure 2.2) e.g., being decoupled from the design process and the need for practitioners to translate between data models, can be overcome.



**Figure 2.2 Tool-box approach (Clarke, 2001)**



**Figure 2.3 Computer-supported design environment approach (Clarke, 2001)**

### **Data model integration**

To achieve the integration of engineering domains it was recognized that the product information needs to be standardized. The idea behind data modeling is to provide a format for product related information allowing its storage, exchange and retrieval (Bakis et al., 2007). Notable early efforts in construction are the AEC Reference Model GARM (Giellingh, 1988) and RATAS (Bjork, 1989). The most prominent current initiative is the development of the Industry Foundation Classes (IFC) under the umbrella of buildingSMART. The green building XML (gbXML) format specifically targets the data provision for energy analysis. It allows the transition of CAD-models to a web-based energy analysis service for fast performance feedback (Yezioro et al., 2008).

The research projects SEMPER 1 & 2 and COMBINE 1 & 2 (1990-1992; 1992-1995) contributed significantly to achieving better functional integration by embracing the existing tool capabilities and making them available to the design team, as in the case of COMBINE, or linking them dynamically to the design alternative, as realized in the SEMPER-project.

The COMBINE project focused on enabling multi-criteria design through the integration of a range of discipline specific tools. The aim was to enable program interoperability so that design support environments evolve in response to interdisciplinary design needs (Augenbroe, 1992).

The SEMPER project was a research project with the goal of expanding the scope of simulation environments. The resulting prototype is dynamically linked to a number of simulation modules. Changes to the design are dynamically mapped to its representation within the design models (Mahdavi, 1999, Lam et al., 2004c).

The design analysis interface (DAI) initiative expands on the limits of data models.

It aims at providing a workbench for managing the sequence of tasks leading to the selection of a specific design alternative (Augenbroe et al., 2004, Wilde and Voorden, 2004). The DAI specifically addressed the need for complex filtering techniques to gain access to the required product information; issues related to data ownership such as maintenance and updating, as well as the perceived rigid order of the model structure.

Sharing simulation models is a recognized alternative to achieving interoperability. The approach aims at the reuse and inter-application of simulation models originating from different tools. Co-simulation is performed to overcome limits in a single tool's capabilities by using model components from others (Trcka, 2008).

## **2.2. Building performance simulation for design support**

In building engineering, information technology offers the unique opportunity to automate complex tasks. Research to support the conceptual design stage focuses on a variety of subjects.

Efforts making use of artificial intelligence to train neural networks for the prediction of specific performance metrics have been reported (Yezioro et al., 2008). Evolutionary computing techniques are proposed to automate the process of generating design alternatives and to facilitate parametric design optimization (Kicinger et al., 2003, Rafiq et al., 2003, Emmerich et al., 2008). To support practitioners in making design decisions, multi-criteria decision making is recognized as a valuable research field (Balcomb and Curtner, 2000, Germano and Roulet, 2006). Furthermore, the provision of design information by enabling direct feedback and conversion of implicit to explicit knowledge is a recognized research domain in conceptual design (Yi-Luen Do, 2005, Hoeben and Stappers, 2005, Hopfe et al., 2006a, Yezioro, 2009).

The potential of computational tools to support design has been recognized more than 30 years ago. Ever since, organizations such as the Building Environmental Performance Analysis Club (BEPAC) and the International Building Performance Simulation Association (IBPSA) have strived to promote and convey the science of building performance simulation to design practice. They acknowledge that computational representations of physical phenomena are the key to performance predictions. Nowadays, a great variety of tools differing in global purpose, degree of model resolution and analysis objective are available.

To evaluate their potential to support the early design stages in practice, interviews were conducted, and a software review and literature survey were undertaken. The work was accomplished in cooperation with Christina J. Hopfe and Gülsu Ulukavak Harputlugil. Results of the work are published in Hopfe et al. (2005) and Hopfe et al. (2006d).

### **2.2.1 Tools for conceptual and detailed design support**

Simulation tools can be categorized based on their potential to support specific design stages in, e.g., conceptual design analysis (CDA) and detailed design analysis (DDA) tools.

DDA-tools are integrated performance simulation tools which address more than one aspect of the building performance, e.g., ventilation, lighting and heating & cooling. Detailed tools require the definition of a great number of parameters to define the building and system model and its use.

CDA-tools are developed using two distinct strategies to reduce the input detail to crucial parameters governing energy demand and/or thermal comfort. One strategy is to abstract the interface by reducing the number of parameters required to define the building and system model; examples are ORCA (Dijk and Luscuere, 2002). Another strategy is to make use of simplified physical models; examples are the MIT Design Advisor (Urban and Glicksman, 2006) and h.e.n.k. (Vabi BV, 2006).

Several problems hindering the application of simulation tools for conceptual design support have been identified. Mahdavi (2005) states that the limited use of simulation tools by, e.g., architects is because the tool is often seen as overly specific and partial in its coverage.

Soebarto and Williamson (1999) appoint out that computational simulation tools are usually used on completed designs, even though the information is incomplete during the conceptual design phase.

In response to the identified problems, Dunsdon et al. (2006) propose a framework that uses tools which are adaptive to the characteristics of the design process.

Ellis and Mathews (2001) recommend the use of sensitivity analysis to reduce the amount of parameters needed to define building models. Their work results in a simplified simulation tool to support architectural design. Examples of applications of the approach are reported by Itard (2003) and Urban and Glicksman (2006).

Whilst simplified tools might prove to be useful at a certain point in the early design, they might be too limited to be applied in later design evaluations.

Lam et al. (2004b) argue that it is beneficial for a tool to remain relevant throughout the process. Based on the review of five tools, Lam et al. confirm the absence of, and need for, facilities to perform parametric studies.

Another aspect also considered by Lam is the need to stimulate collaborative working in integrated teams. Lam et al. (2002) suggest the use of web-based services to allow platform-independent and distributed collaboration.

### **2.2.2 Practitioners perspective**

To gain insight into what practitioners require with respect to computational support during conceptual design, interviews were conducted.

The interviews were held with fifteen HVAC consultants from internationally operating engineering firms such as Arup, Buro Happold, Faber Maunsell AECOM, Royal Haskoning, Deerns and HALMOS, of whom six were mechanical engineers, two building physicists, two architects and one a civil engineer. Twelve of the interviewees are practitioners with extensive industrial experience, whilst the remaining three work in academia.

The aim was to obtain cross-disciplinary expert knowledge regarding the conceptual design stage and to identify the issues that hinder the application of building performance simulation. The varying disciplines of the participating experts and place of activity (Netherlands and UK) did provide insight into the current challenges and development foci of the architecture, engineering and construction industry. Interviews can be conducted in two fundamental different forms: structured and unstructured.

*Structured interviews* are based on a list of prepared questions. The analysis of results is straightforward as the feedback format is similar and can be used for quantitative analysis. The disadvantage is that the scope is fixed and deviation to related subjects is limited.

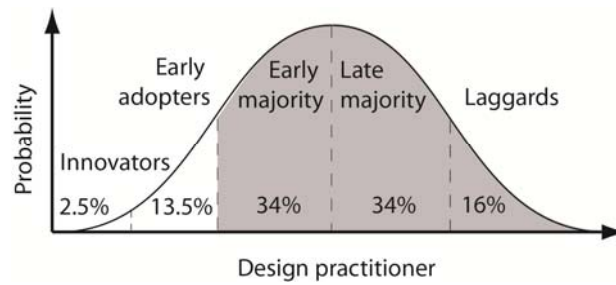
*Un-structured interviews* require the formulation of a number of key-aspects to guide the interviewee. This form does allow deviation from the core subject in order to explore a range of related aspects. The disadvantage is that the feedback is in a non-uniform format, which complicates a quantitative analysis.

Unstructured interviews were conducted. They are the most appropriate surveying technique for the present study, as they provide flexibility to explore the views, opinions and feelings of forward thinking practitioners on the use of building performance simulation in conceptual building design. The audio track of the interviews was recorded for reference. The following key-aspects were discussed:

1. Introduction and definition of role in design projects,
2. Problems repeatedly encountered during the early design stages,
3. Experiences using computational tools to support building design, in particular in the conceptual design stage, and
4. Issues that future design support tools should address.

The interviews evolved around three main themes; (1) computational performance evaluation (2) design integration of disciplines, and (3) performance communication.

To enable a statement about the practitioners' focus on the three themes, Roger's (2003) categories of adopters of innovations were applied. The focus was thereby on the forward thinking practitioners: innovators and early adopters see Figure 2.4.



**Figure 2.4 Categories of design practitioners, adapted from Rogers (2003)**

The conclusions from the obtained feedback are that practitioners can be categorized as laggards for one theme and innovators for another; see Appendix A, Table A.7.4 in the appendix.

A relationship was observed between computational performance evaluation and performance communication, as well as between design integration of disciplines and performance communication.

The observations indicate that although industry practitioners focus on improving integration of design disciplines, they do not necessarily conclude that enhancing the use of computational performance evaluation would be valuable. However, practitioners focusing strongly on communicating the building performance do consider the use of computational performance simulation as important.

#### ***Qualitative aspects related to the tool use in conceptual design***

The following qualitative points are considered relevant for facilitating computational support in the early design stages. They are summarized in design requirements, design process, generation and selection of design alternatives as well as use of computational tools.

##### *Design requirements*

Depending on their engineering discipline, the interviewees value design requirements differently. Design requirements discussed are costs, spatial flexibility, thermal and acoustic comfort, energy consumption, indoor environmental quality, sustainability and productivity.

##### *Design process*

The majority of interviewees understand the design process to consist of different stages. They agree upon the fact that the most important phase is the early conceptual design stage because of the impact of decisions on the final building performance. A limited number of interviewees perceive design development as a process with no clearly defined phases. The process is perceived as unstructured and iterative.



For most interviewees an integrated design team is the most suitable forum to develop complex building systems. It is considered beneficial to integrate all team members from the beginning of the design process.

Synchronization of the design development across disciplines is perceived as advantageous. Most interviewees agree that the project kick-off should be the same for all parties. The interviewees draw attention to the fact that consultants are often invited late, resulting in sub-optimal design solutions.

#### *Generation and selection of design alternatives*

The interviewees generate design alternatives differently. The use of sketches and drawings is common practice. The use of simulation tools is also reported for concept generation. Dependent on the scope of the discussion they cover either parts or the whole building. The interviewees agree that the number of design alternatives developed is higher for complex tasks.

Interviewees emphasize that design teams run the risk of limiting themselves too early to an insufficient number of design alternatives, resulting in the decision for a sub-optimal design. It is common practice to develop more than one design alternative. To evaluate and select design alternatives, performance requirements are used. Performance requirements are discipline and project specific.

#### *Use of computational simulation tools*

Design communication has different characteristics during early and late design stages. During early design stages communication is informative, whilst in late design stages communication is descriptive. Lack of communication is perceived as a major problem for design integration.

Three of the interviewees explicitly exclude the use of computational simulation tools for reasons such as: limited exposure, lack of confidence in simulation results and a steep learning curve.

The majority of the interviewees agree that the use of simulation tools should be facilitated in the beginning of the design process to supplement design experience and knowledge and thus improve the design making process.

One problem of tools dedicated to the conceptual design stage is that most of them request extensive input data, and address only a limited number of performance requirements. Computational tools are recognized to enable an assessment of the relative impact of design parameters. Absolute simulation results are considered dubious as the model cannot be calibrated against measured data.

### ***Potential and limits for computational simulation by design practitioners***

The practitioners identified a number of points that when addressed during the development of new tools provide potential to add value during conceptual design:

1. The interviewees agree that computational performance simulation has the biggest impact on design when applied early complement design experience.
2. Particularly for complex design problems, computational simulation shows potential to provide feedback quickly for a great number of design alternatives by assessing the relative impact of design parameters on set performance requirements.
3. Simulation results provide quantitative information to aid the communication of the performance of design alternatives.

The key items that hinder the enhanced use of computational simulation tools during conceptual design from the perspective of design practitioners are:

1. State of the art simulation tools are limited in scope with regards to the addressed performance requirements.
2. Current tools are only used to assess the relative impact of design parameters. Confidence in absolute results of performance prediction is limited.
3. The available tools are perceived to be too detailed. The required design information necessary to define a building model during the conceptual design stage is not available at the time.
4. Tools should be usable and intuitive. This requires functions and features such as 3D modeling, copy/ past and undo, as well as interfaces that are adaptable to the design stage; reuse of parts of past project models.
5. Also, the tools should be able to deal with complex physical phenomena and represent innovative building services systems.

### **2.2.3 Simulation tool capabilities**

To verify the practitioners' view on computational simulation tools, a critical software review was conducted. The aim was to gain hands-on experience with the use of the tool for conceptual design. Six tools were considered (A) Orca, (B) MIT Design Advisor, (C) h.e.n.k., (D) Energy 10, (E) Building Design Advisor and (F) e-QUEST, see Appendix B – Software.

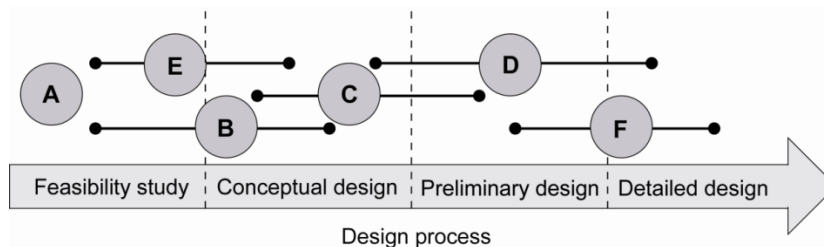
The tools are a representative sample from the pool of commercial and academic state of the art building performance software. The tools cover local and international developments and claim to serve the conceptual design stage. The perspective was of an integrated design team searching for the most favorable design solution.

The final design was required to comply with set performance requirements. It was appreciated that the performance of the design solution would be a compromise between the different defined performance requirements. Furthermore, it was idealized that the design disciplines were synchronized with regards to simultaneously working on the conceptual design.

Two representative buildings were chosen as design cases – a one-family home and an office building. The buildings are characterized by a number of special features. The office building design implements a double skin façade, atrium and full air conditioning system. The residential building design comprises special features such as a pitched roof and a double-height living room. A more detailed description of the approach, the case studies and results can be found in Harputlugil et al. (2005).

The target was not to compare the results of the study quantitatively but to evaluate the tool with respect to: model testing and validation, building modeling, defaulting, calculation engine, design optimization, representation of results.

The key result of the review is that only four of the six tools have the potential to support the conceptual design stage, see Figure 2.5.



**Figure 2.5 Tools potential to support conceptual design**

Results of the work were published earlier in Hopfe et al. (2006c) and (2006d). The following passages address the evaluation criteria individually.

#### *Testing and evaluation*

Five of the six tools are validated either by the BESTEST procedure (Judkoff and Neymark, 1995) or by EDR tests (ISSO, 2007). No information about testing of the tools on the user group could be identified.

#### *Building modelling*

The building modeling capability varies from one representative room only, to the definition of thermal zones on the room level; tools (E, F).

Due to modeling limitations, not all tools allow the definition of features such as double-skin façade or atrium and tilted roof. B and D have the option to represent a double-skin façade.

Tool C gives the possibility to define a tilted roof. Due to hidden default values, not all tools allow the performance evaluation of residential buildings. Tools A and C only provide features for modeling offices.

#### *Defaulting*

Three of the tested tools have extensive databases providing default values for the given input requirements. One tool (A) has no such feature for the HVAC components present. However, due to its limited capabilities in representing HVAC systems, it is not required. Another tool (B) requires the user to manually input the required parameter. It is possible to refer to example models for verification. Tool E lacks a defaulting feature for defining internal loads and HVAC systems. Nevertheless, the material database contains predefined transparent and opaque building components which can be used for the model set up. The defaulting features of the tools are far from intelligent as they do not suggest settings or combinations of settings.

#### *Calculation engine*

Three tools use unique application based calculation engines and some act as an interface to high resolution engines. Still, the model exchange to higher resolution modeling is facilitated only in the case of tool F.

#### *Optimization*

Once the most appropriate building concept has been chosen an optimization process could be initiated to identify optimum values for selected design parameters. Three of the six tools (B, C, D) offer optimization features.

#### *Representation of results*

The capability to directly compare results for different design alternatives is a useful feature for the conceptual design stage. Four of the six tools (B,D,E,F) provide the feature for up to four design alternatives.

#### ***Limits of simulation tools to support integrated design teams***

The following aspects were found to hinder the uptake of computational simulation during conceptual design.

1. The use of vocabulary and level of detail required for the representation of systems for four of the six packages identified their origin as being developed for mechanical engineers from the perspective of mechanical engineers.
2. The six tools only address performance requirements related to the consequences of the interaction between building structure and building systems. Performance requirements related to architecture and/or structure are not addressed.

3. The tools can be used to support the following applications, traditionally tasks by building services engineers: energy calculation, comfort assessment, life cycle costing, artificial and day lighting assessment and code compliance checking.

4. The number of building services systems that can be modeled is limited. No features were observed that allow the system libraries to be extended manually.

5. The definition of double-height spaces and atria is possible in only two of six tools. Further, calculating bulk airflow problems and the interaction between open plan office areas and atria is only possible in one of six programs.

6. The support provided to identify crucial performance governing parameters and system components is limited. Four tools allow the visual on-screen comparison of up to four design alternatives. This is too limited to establish the dynamic building response to parameter and system variations.

7. Limited support is provided for multi-criteria decision making. The designer is left to interpret the complex results and to draw conclusions.

#### **2.2.4 Requirements on simulation tools**

The results of the documented interviews, software review and literature survey indicate that computational simulation is primarily used to evaluate and communicate the performance of design alternatives. The industry representatives clearly indicate the importance of working in integrated teams as this has the biggest potential to conserve resources. However, working in an integrated manner also requires taking into account performance requirements from other engineering disciplines.

The review of the state of the art indicates the need to expand the capabilities of existing tools with respect to quality assurance and concept development. To facilitate use, the tool has to fit the character of the design stage and the needs of the involved engineering disciplines. The most prominent identified requirements for computational simulation tools in the early design stages are:

- A flexible tool structure to facilitate expanding the system representations with innovative design concepts, potentially object oriented as is the case with TRNSYS.
- A facility for the quick generation of integrated design alternatives.
- Enable dynamic scaling of model resolution to fit the different levels of information density.
- Enable parametric studies to support generating design alternatives, by providing a measure of sensitivity.

- A facility to explore the consequences of design decisions on performance aspects based on the performance uncertainty due to the uncertainty in design parameters.

### **2.3 Uncertainty propagation and sensitivity analysis**

Sensitivity analysis is reported as a measure to limit the tool complexity for the needs of the early design stages (Ellis and Mathews, 2001). However, reducing the complexity of a detailed tool also limits its applicability during the later design stages. To allow adaption of detailed tools for the conceptual design stage, the author suggests the iterative use of sensitivity analysis during the design process.

Design decisions taken during the conceptual design stage have a disproportional impact on the final building performance. This causes the risk of the building performance failing to meet the performance requirements, especially as early design decisions are often based on incorrect, incomplete or highly complex information.

To quantify the probability of the system exceeding its performance limits due to the uncertain model input, it is proposed to propagate the uncertainty through the simulation model and establish its effect on the output (Macdonald, 2002b).

Different sources of uncertainties exist in performance simulations. De Wit (2001) differentiates between four categories: specification-, modeling-, numerical-, and scenario uncertainties, see Table 2.1.

**Table 2.1 Categories of uncertainties in building simulation**

Specification	Incomplete specification of input parameters such as material properties
Modeling	Assumption and simplification of physical processes
Numerical	Discretization of space and time
Scenario	External conditions and occupancy pattern

The uncertainty categories which relate to conceptual design are specification, modeling and scenario uncertainties. It is assumed that when choosing an appropriate temporal and spatial discretization, the numerical uncertainty becomes insignificantly small.

### **2.4 Concluding remarks**

Building regulations are evolving from prescriptive to performance based. This in turn requires changing the building design focus from purely defining input specification to fulfilling the set user requirements. Those developments require a stronger integration of design and evaluation. The potential for computational support to provide design guidance is especially high during conceptual design.

Interviews with practitioners indicate the need for a better integration of design disciplines and better communication of performance. Although industry practitioner's focus on improving integration of design disciplines, they do not automatically favor enhancing the use of computational performance evaluation.

However, practitioners focusing on communicating the building performance consider the use of computational performance simulation important.

Some interviewees perceive design development as a process with no clearly defined phases. The process is perceived as unstructured and iterative. Furthermore, they believe that their contributions are invited too late in the design process.

The interviewees agree that the number of design alternatives developed is higher for complex tasks. Design teams limiting themselves too early to an insufficient number of design alternatives run the risk of choosing a sub-optimal design.

Design communication has different characteristics during early and late design stages. The interviewees agree that the use of simulation tools should be facilitated in the beginning of the design process in order to supplement design experience.

However, the available tools are perceived to be too detailed. The design information necessary to define a building model during the conceptual design stage is not available at the time.

Tools for the early design stages are required to have flexible tool structure to facilitate expanding the system representations with innovative design concepts. They are required to provide facilities to explore relationships between design decisions and performance aspects, enable parametric studies and be able to dynamically scale the model resolution to fit the different levels of information density. Uncertainty propagation and sensitivity analysis are proposed to provide those capabilities.

Simulation environments that quantitatively address uncertainties and sensitivities related to building design and operation are expected to have the potential to (1) provide an indication of the accuracy of the performance predictions; (2) allow the identification of parameters and systems to which performance metrics react sensitively and in-sensitively, respectively; and (3) enable a robustness assessment of design alternatives.

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# 3

## Uncertainty propagation and sensitivity analysis with BPS-models

The previous chapter concludes that information about the uncertainty of performance metrics and their sensitivity to design parameters and subsystems has the potential to add value to the design process. Information about uncertainties and sensitivities of simulation output can support the selection of design alternatives and provide design guidance by complementing the design experience of practitioners. To generate this information, state of the art tools need to be expanded with additional analysis techniques. The aim of chapter three is to identify and evaluate means to facilitate uncertainty propagation and sensitivity analysis. The main research questions are:

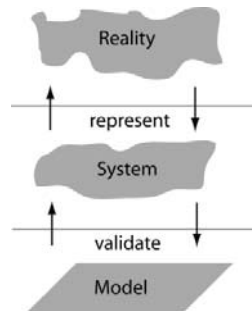
1. How can the probability of performance failure be quantified in terms of uncertainty?
2. Which techniques are applicable to facilitate uncertainty propagation and sensitivity analysis for the performance evaluation of virtual building models using state of the art simulation tools?
3. What procedure allows the implementation of uncertainty propagation and sensitivity analysis with state of the art simulation tools while accounting for the characteristics of analysis techniques and requirements of design practitioners during conceptual design?

The questions are addressed by means of literature review, iterative prototyping and computational experiments. The work required the review of frameworks for mapping risk and uncertainty; a review of techniques for the quantitative assessment of parameter uncertainties and sensitivities; the formulation of a prototyping methodology, as well as its implementation, verification and testing.

The work is documented in logical order. First, analysis techniques are reviewed and evaluated, the most suitable technique is then implemented into a computational prototype. Thereafter, the prototype is tested on two tools, a conceptual design analysis tool and a detailed design analysis tool in order to identify their potential to provide design support.

### **3.1 Uncertainties in model predictions**

Models are validated physical, or mathematical system representations of real world entities, phenomena or processes, see Figure 3.1.



**Figure 3.1 Model, System & Reality [from Vissers and Vries (2005)]**

The use of models has the following advantages:

- Models allow local or global optimization of parameters.
- Models permit performance predictions to be made.
- Models allow operational sequences to be derived.

Models will rarely give perfect representation of empirical data. In most cases there will be differences between model predictions and data, see formula (1). Miles and Shevlin (2001) argue that a perfect model is not a model but a duplicate.

$$DATA = MODEL + ERROR \quad (1)$$

Modeling techniques, such as simulation, allow the physical product to be visualized and evaluated prior to design decisions. The Defense Acquisition University (2001) states:

*“A simulation is the implementation of a model over time. A simulation brings a model to life and shows how a particular object or phenomenon will behave. It is useful for testing, analysis or training where real world-systems or concepts can be represented by a model.”*

The benefit of using simulations during design is the rapid and quantitative assessment of performance, costs and subsequently risks during life cycle activities. Relevant literature associates risk with uncertainty and ignorance; see, Knight (1921), Mayumi and Giampietro (2001), Stirling (1998) and Dessai and Hulme (2003). Mayumi and Giampietro (2001) define risk and uncertainty following Knight (1921) as follows:

*“Risk is defined as situation in which the distribution of the outcome in a group of instances is known either from a priori (we have a reliable model of the mechanisms generating the outcome) or from statistics (we can use our knowledge of frequencies to infer probabilities), whilst uncertainty represents a situation where it is impossible to form a reliable group of instances because the situation is in a high degree unique.”*

Their definition of risk relates to uncertainty, which conforms well to what Hoffman and Hammonds (1994) or Kirkup and Frenkel (2006) refer to as type A and B.

In contrast to relating risk purely to uncertainties, this thesis follows the definition of risk by Ale (2009), who defines risk as the product of probabilities and consequences, see (1). Risk  $R$  is thereby the total value of expected outcomes  $p$  multiplied by the consequence  $c$ .

$$R = p * c \quad (1)$$

Helton et al. (2006) refer to aleatory and epistemic uncertainties. In the current work we use the vocabulary most commonly used in discipline specific literature, aleatory and epistemic uncertainties.

The *aleatory* uncertainty represents a range of “degrees of belief” that the true but unknown value of the parameter is equal to or less than that of any value selected from a distributed parameter. It can originate from measurements or model predictions and is represented by a probability distribution.

*Epistemic* uncertainties are characterized by a lack of knowledge about the actual probability distribution of the parameter. Hoffman and Hammonds (1994) give an example of how to resolve the lack of knowledge by assuming a number of “subjective” probability distribution for the parameters mean value and standard deviation. Those distributions samples are taken to arrive at aleatory probability distributions of which samples are taken for the uncertainty propagation.

To quantify epistemic uncertainties Stirling (1998) & Dessai and Hulme (2003) follow Knight’s (1921) suggestion to use probability based methods, such as frequentist and bayesian distribution functions, whereas scenario analysis is suggested for the assessment of aleatory uncertainties.

The increasing use of building simulation to support design has also raised awareness of uncertainties in model predictions (Lomas and Eppel, 1992, Clarke, 1998, Macdonald, 2002a, Corrado and Mechri, 2009). De Wit (2001) identified four types of uncertainties in building simulation: numerical, scenario, modeling and specification.

*Numerical uncertainties* are introduced by the choice of temporal and spatial discretization. Numerical uncertainties are not further considered here as they are assumed to be made arbitrarily small when choosing the appropriate model discretization.

*Modeling uncertainties* are introduced by simplifying models of physical phenomena and processes as well as building and system components.

*Specification uncertainties* arise from incomplete information about the integrated building system under consideration.

*Scenario uncertainty.* The choice of scenario within which the building is supposed to operate also contributes to the performance uncertainties. Scenarios typically describe dynamic external and internal loads on the integrated building system. The assessment of scenario uncertainties provides information about the robustness of the design.

Both modeling and specification uncertainties are of particular interest for performance evaluations during conceptual design as little detail is available at that time about the building specification and final physical appearance. Specification uncertainties can originate from at least two sources, activities related to specifying physical properties of the building material -*physical uncertainties*-, and from design activities, such as choice of HVAC concept, arrangement of rooms and window dimensions, -*design uncertainties*.

### **3.2 Applied sensitivity analysis and uncertainty propagation**

In design practice engineers increasingly use simulation models to assess the performance of buildings. In many cases the relative difference of model output is evaluated to learn about the building's response to variations of design parameters. The assessment allows the identification of the input parameter combinations, which ensures the required performance. The process is constrained by the costs of simulations.

The process requires multiple simulation runs. From such results, HVAC consultants derive design guidance in the form of: "*Limiting the peak capacity of the cooling coil to x%-percent of the peak cooling load results in the y more overheating hours*".

The absolute model output is rarely used for design as it is not possible to calibrate the simulation model. The process aiming to quantify the influence of model parameter on the model output is referred to as *sensitivity analysis*. Its practical value in engineering lies in its ability to support, e.g.: parameter screening, robustness assessment and parameter accuracy evaluation.

*Parameter screening:* Models in engineering (environmental, mechanical or building etc.) are often complex, with more than  $10^3$  in- and output parameters. Sensitivity analysis allows for screening of the input parameters to identify the few which dominate the variation in the output.

*Robustness assessment:* If performance limits for a system are defined, sensitivity analysis provides information about the magnitude of performance changes due to variations of input parameters, which helps to maintain the required performance.

*Parameter accuracy necessity:* If a model output reacts sensitively to a specific parameter's uncertainty estimate, it needs to be determined with a higher accuracy level.

The observed ad-hoc approach to sensitivity analysis (SA) in current design practice has two distinct characteristics: (1) it is based on varying a limited set of parameters one at a time (OAT) and (2) it is restricted to a narrow search space - local sensitivity analysis. The application of OAT and local approaches poses the risk of overlooking influential parameters, of influencing parameter interactions and of considering a too limited parameter range.

Different to local SA approaches, Saltelli et al. (2004) introduce "*global sensitivity analysis*". Global sensitivity analysis is defined as:

*"The study of how uncertainty in the output of a model (numerical or otherwise) can be apportioned to different sources of uncertainty in the model input."*

Uncertainty analysis is closely related to sensitivity analysis as it aims to quantify the overall uncertainty in the model response due to the collective uncertainty in the model input (Saltelli et al., 2008). It is recommended to investigate parameter sensitivities if the model output uncertainty is outside acceptable bounds. Hence, it is recommended to precede a global sensitivity analysis with an uncertainty analysis.

A multitude of approaches and metrics are suggested for sensitivity analysis, see Lomas and Eppel (1992), Hamby (1995), Fürbringer and Roulet (1995) and Helton et al (2006).

It is advantageous to use the same technique for both types of analysis; uncertainty propagation and sensitivity analysis. To narrow the search for appropriate approaches, their application was reviewed and criteria were defined to assist the selection. The following five criteria were identified (Saltelli et al., 2004, Ravalico et al., 2005) and used to select an appropriate approach for uncertainty and sensitivity analysis for conceptual design support:

- Ability to cope with scale and shape of input parameter distributions;

The selected approach should be able to cope with the influence of scale and shape of the input parameter distribution. The global effect of the parameters' influence on the output can only be evaluated if the probability density function's range and form can be fully represented.

- Capacity to account for simultaneous variations of parameter values;

Whilst OAT approaches compute partial derivatives, the effect of the variation of a parameter when all others are kept constant, "concurrent" approaches allow the evaluation of the effect of a parameter while all others change as well.

- Model independency with respect to parameter interaction, non-linearity and non-monotonicity;

The approach is required to work regardless of parameter interactions, non-linearity or non-monotonicity of the model. Parameter interaction occurs when the effect of changing two parameters is different than the sum of their individual effects.

- Ability to treat grouped parameters;

The approach should allow the exchange of components and building subsystems by aggregating input parameters. This feature eases the focusing of the data analysis on the essential details.

- Provision of useful input for decision making.

For the output of uncertainty and sensitivity analysis to be useful for decision making, it is assessed by its potential to convey a physical meaning (design information). That is, by estimations of values a (output-) parameter might take, parameter quantification or by providing a basis for predictions.

The integrated consideration of Latin hypercube sampling and correlation & regression analysis aims to provide both estimations of the model output uncertainty and parameter sensitivity (Saltelli et al., 2006, Helton et al., 2006).

### **3.3 External techniques for uncertainty and sensitivity analysis**

Considering the state of the art simulation tools, two fundamentally different approaches for uncertainty propagation can be differentiated; internal and external (Macdonald, 2002a). The two approaches differ with respect to the place where the definition of input parameter uncertainties takes place; internal or external to the simulation model.

The use of internal methods requires adapting the model source code to propagate the uncertainty for each simulation step. The advantage is that only one simulation is required to estimate the uncertainty of the model output (Macdonald, 2002a). There are two reasons for using an external technique: (1) detailed knowledge about the structure of the source code and underlying physical models and (2) restricted access to source code for commercial tools.

The application of external techniques allows applying the probabilistic approach. The probabilistic approach requires multiple simulations with different values for the input parameters. The analysis typically requires a five-step procedure (Helton et al., 2006, Saltelli et al., 2004).

1. Definition of the distributions to characterize the uncertainty in the model input.
2. Generation of a sample matrix.
3. Uncertainty propagation.
4. Approximation of the distribution of the model output and presentation of the uncertainty analysis results.

5. Determination of the sensitivity statistics.

**3.3.1 Differential sensitivity analysis**

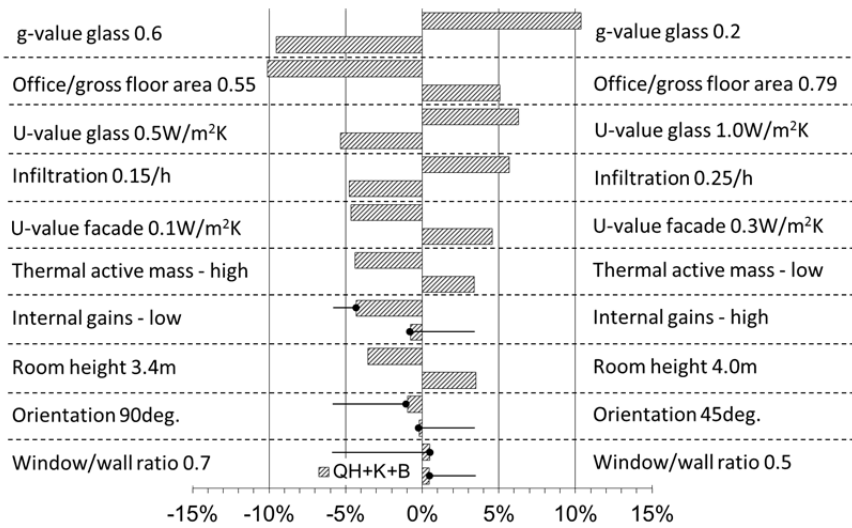
The most commonly considered method for sensitivity analysis is Differential Sensitivity Analysis (DSA) (Lomas and Eppel, 1992, Lam and Hui, 1996, Tavares and Martins, 2007). Attia et al. (2012) propose the use of differential sensitivity analysis to educate architects during the conceptual design stage. It enables an instantaneous exploration of changes in the output due to changes in the input. At first, a simulation is conducted with all variable parameters at their base value. For each of the following simulations, one variable parameter is changed. The change of the output can be directly related to the input, and the interpretation of the results is straightforward. Suitable assumptions of the input parameter range allow estimates of the output uncertainty to be calculated. The required number of model runs depends on the number of cases  $C$  (base case, minimum value, maximum value) and the number of parameters  $n$  considered.

$$N = 1 + (n \times C) \quad (2)$$

The differential sensitivity analysis does not provide information about the cumulative parameter impact.

As an example, the sensitivity of the energy demand of an inner city office building to ten parameters is analyzed. The considered parameters were selected in a multidisciplinary workshop. The parameter base values as well as minimum and maximum values are based on published data. See Struck et al (2011) for more information on the analyzed case. For parameter values see Appendix B, Table B 7.5.

Results from a differential sensitivity analysis are typically represented in bar charts. The bar represents the impact of the analyzed parameter change relative to the reference case, see Figure 3.2. The bar also provides information about the direction of impact, positive or negative.



**Figure 3.2 Percent change from base case as sensitivity measure for performance indicator energy use for heating, cooling and artificial lighting.**

### 3.3.2 Monte Carlo analysis

Monte Carlo analysis is a technique used to support uncertainty propagation and is based on sampling parameter ranges acting as simulation input (Billinton and Li, 1994, Kurowicka and Cooke, 2006, Saltelli et al., 2008). It is an approach to represent the scale and shape of the parameter’s probability density function. Monte Carlo analysis has become a synonym for sampling based analysis procedures.

It is based on sampling multiple input parameters to generate a matrix  $M_{nk}$ , with  $n$  the number of input parameter and  $k$  the sample size. The model output is evaluated for each matrix element  $x_{ij}$ . The output vector  $Y = [y_i]$  is generated according to (3):

$$y_i = f(x_{i1}, x_{i2}, \dots, x_{in}) \quad i = 1, 2, \dots, k \quad (3)$$

Conventional sampling approaches e.g., random or brute force, require repeated sampling from assumed joint probability distributions of the parameter ranges  $X$  and evaluation of the distribution of  $Y$  and its statistical characteristics.



### Latin Hypercube sampling (LHS)

Compared to random sampling the constrained Latin hypercube sampling (McKay et al., 2000) is an efficient method for computationally demanding models.

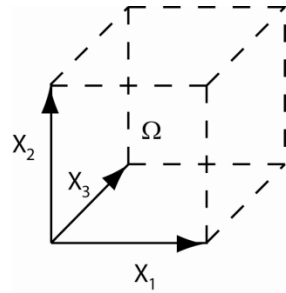
This is because of its efficient stratification properties (Saltelli et al., 2004, Helton et al., 2006, Corrado and Mechri, 2009). It allows the extraction of a large amount of uncertainty and sensitivity information with a comparably small sample set. LHS selects  $n$  different values from each of the  $n$  parameter range  $X_1, X_2, \dots, X_k$ . The range of each parameter  $X$  is divided into  $n$  non-overlapping intervals with equal probability. One value from each interval is selected randomly. The  $k$  values for  $X_1$  are randomly paired with the values for  $X_2$ . These pairs are randomly paired with the values for  $X_3$ . The process continues until a  $n \times k$  sample matrix is formed.

Although the sample matrix is formed by random pairing, the correlation coefficient of the  $k$  pairs of factors will not equal zero due to sampling fluctuations (Swiler and Wyss, 2004). It is typically assumed that input parameters are independent. For models for which the independency assumption is not considered appropriate, methods exist to direct the pairing process which results in the desired correlation structure. Iman and Conover (1982) propose the use of rank correlation.

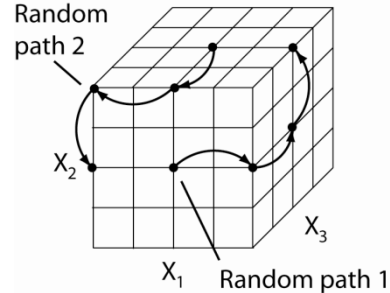
Latin hypercube sampling provides a good basis for uncertainty analysis considering all input parameters. However, as a sampling based analysis it creates a fluctuating convergence process, meaning that the confidence range decreases as the number of samples increases. Lomas and Eppel (1992) as well as Macdonald (2002b) suggest 60-80 model evaluations above which no great improvements of the accuracy can be achieved. The use of statistics allows parameter sensitivities to be derived from the simulated data (Saltelli et al., 2008). Different statistics are suggested for that purpose.

#### 3.3.3 Morris method

The method of Morris, a sampling based procedure, is used to establish which model input parameters  $X$  have effects on the model output  $Y$ . The effects on the model output can be negligible, linear and additive, or none-linear, or involved in interaction with other parameters (Morris, 1991). It therefore uses a specific sampling scheme to match the requirements of the analysis procedure (Wit, 2001, Heiselberg et al., 2009, Corrado and Mechri, 2009). The impact of each factor on the performance metric is expressed by the mean value and standard deviation of its elementary effect  $d_i$ . To arrive at the elementary effect the region of experimentation  $\Omega$  is defined by the number of parameters and their range, see Figure 3.3.



**Figure 3.3 Morris analysis, Region of experimentation defined by three parameters**



**Figure 3.4 Morris analysis, Representation of a five-level grid with three parameters and two trajectories**

Each model parameter is scaled 0 to 1, The region of interest for each parameter is discretized in a p-level grid, (see Figure 3.4.) whereby  $\Delta$  is predetermined multiple of  $1/p - 1$ , see (4).

$$d_i(x) = \frac{[y(x_1, \dots, x_{i-1}, x_i + \Delta, x_{i+1}, \dots, x_k) - y(x)]}{\Delta} \quad (4)$$

The elementary effect of one parameter within one trajectory is the change of the output variable divided by the scaled change of the input parameter, step size. Each trajectory provides one value for the elementary effect for each input parameter. The mean value and standard deviation across the calculated elementary effects gives the sensitivity measure; see the example below. The parameter range and distributions as well as a section of the samples can be found in Appendix B, Table B 7.6. and Table B 7.7.

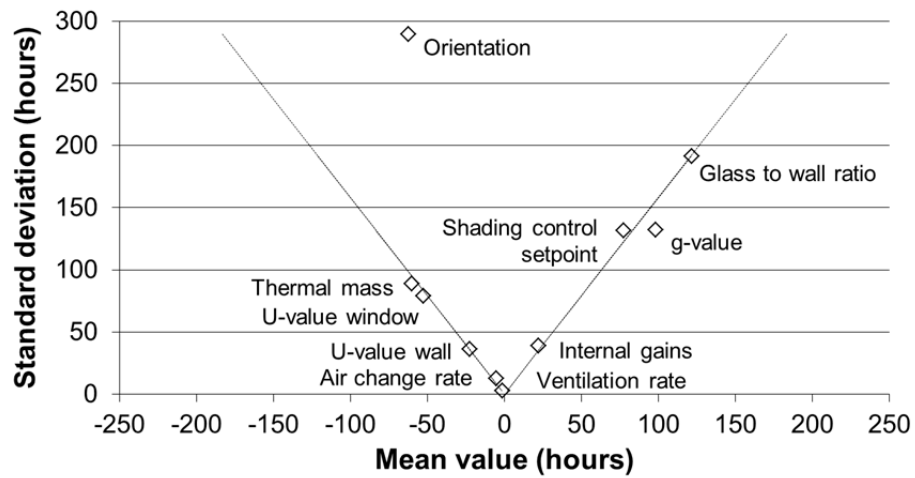
The example below for the Morris analysis is to show how insight is gained into the individual effect of ten parameters (see Appendix B, Table B 7.6) on the violation of the adaptive temperature limit of 80% for an office room.

**Table 3.1 Analysis settings**

Setting	Value
Number of Parameters	10
Grid level	6
Trajectories	10
Step size	0.5

**Table 3.2 Exemplary calculation of the elementary effect for two of ten trajectories for ATG 80%**

Sample	Simulation results (ATG80%)	Parameter name	Parameter change	ATG80% change	Step size	Elementary effect
1	0	/	/	/	/	/
2	0	Air change rate	-0.065	0	-0.5	0
3	0	Louvres settings	-175	0	-0.5	0
4	0	U-value window	0.35	0	0.5	0
5	0	U-value wall	-0.15	0	-0.5	0
6	0	Orientation	179.5	0	0.5	0
7	0	Internal gains	-352.5	0	-0.5	0
8	1	Mass	1	1	0.5	2
9	19	g-value	0.2	18	0.5	36
10	19	Ventilation rate	-34.5	0	-0.5	0
11	0	% glass to wall	-30	-19	-0.5	38
12	0	/	/	/	/	/
13	142	% glass to wall	-30	142	-0.5	-284
14	22	Louvres settings	-175	-120	-0.5	240
15	7	Mass	1	-15	0.5	-30
16	4	U-value window	0.35	-3	0.5	-6
17	2	Orientation	179.5	-2	0.5	-4
18	0	g-value	-0.2	-2	-0.5	4
19	0	Internal gains	-352.5	0	-0.5	0
20	0	Ventilation rate	34.5	0	0.5	0
21	0	U-value wall	0.15	0	0.5	0
22	0	Air change rate	0.065	0	0.5	0



**Figure 3.5 Mean value & standard deviation of elementary effect as sensitivity measure for the performance metric ATL80%.**

The method of Morris provides information about the uncertainty of the model output due to changing individual model input parameters. It does not provide an indication of the output uncertainty. The required model runs  $N$  depend on the number of input parameters  $n$  and trajectories  $t$  considered. The number of model runs can be calculated as indicated in (5):

$$N = t(n + 1) \quad (5)$$

The use of mean values and standard deviation for reporting the elementary effects is limited suitable as it suggests a normal distribution. Although inter-quartile range and median are of little arithmetic use, they have better descriptive properties.

### **Descriptive statistics**

Descriptive statistics facilitate compiling major attributes of a data set using measures such as the mean, mode, median, inter-quartile range and standard deviation. Different to inferential statistics, these measures provide a basis for interpretation and understanding of the studied data set within its context.

To interpret results from a Morris analysis applying the mean value  $\mu$ , see (6), and standard deviation  $\sigma$ , see (7), are used.

$$\mu = \frac{1}{n} \sum_{i=1}^n y_i \quad (6)$$

$$\sigma = \sqrt{\frac{\sum_{i=1}^n (y_i - \mu)^2}{n}} \quad (7)$$

Standard deviation and variance are closely related as the variance  $SS$ , also referred to as sum of squares, is the square root of the standard deviation. The variance is an amount of variability of a factor, indicating how much its scores deviate from the factor mean. To characterize the relationship between data sets, correlation and regression coefficients are used.

### **Inferential statistics**

Inferential statistics are useful to model patterns, judge data, identify variable relationships, and deduce characteristics of populations from smaller sample sets. Common inferential statistics are correlation and regression coefficients, among others (Dumas and Redish, 1999).

### 3.3.4 Correlation and regression

Correlation and regression are extensively used techniques to arrive at measures for uncertainty and sensitivity (Saltelli et al., 2008, Saltelli et al., 2006, Saltelli et al., 2004). In many cases the correlation and regression coefficients are used. The coefficients describe the relationship of sampled data and allow inferring characteristics to the population from which the sample was taken.

#### Correlation

The most prominent correlation coefficients, Pearson product moment correlation coefficient, partial correlation coefficient and rank-order correlation coefficient, are discussed below.

##### *Pearson product moment correlation coefficient*

The most common measure of linear correlation is the *Pearson product moment correlation coefficient*  $r$ . The correlation coefficient is the ratio of observed covariance and maximum possible positive covariance between the variables  $X$  and  $Y$ , see (8). It can vary between +1,0; perfect positive correlation; and -1,0; perfect negative correlation. It indicates the direction of correlation. The midpoint 0 corresponds to the complete absence of correlation.

$$r = \frac{SC_{XY}}{\sqrt{SS_X \times SS_Y}} \quad (8)$$

Covariance is a measure of the degree to which two variables,  $X$  and  $Y$ , vary together. The *observed covariance*  $SC_{XY}$  is the amount of covariation that is observed between  $X$  and  $Y$ , see (9).

$$SC_{XY} = \Sigma (x_i - \bar{x})(y_i - \bar{y}) \quad (9)$$

The *maximum possible positive covariance* is the amount of covariation that would be noticed if  $X$  and  $Y$  were perfectly positively correlated. The maximum possible positive covariance between the variables equals the geometric mean of the corresponding variances  $SS_X$  and  $SS_Y$ , see (10) as an example of  $SS_X$ . The geometric mean is the  $n^{th}$  root of the product of those.

$$SS_X = \Sigma_i (x_i - \bar{x})^2 \quad (10)$$

The squared correlation coefficient  $r^2$ , referred to as *coefficient of determination*, indicates the strength of correlation. It can vary between 0 and 1. Multiplied by 100, it gives the percentage of which the variability of the independent variable explains the variability in the depended variable. Tabak (2009) qualifies correlation coefficients based on Guilfort and Fruchter's work (1977) as indicated in Table 3.3 below.

**Table 3.3 Qualification of correlation coefficients (Tabak 2009)**

Qualification	Correlation coefficient (absolute numbers)
Very weak correlation	< 0.2
Weak correlation	0.20 – 0.40
Moderate correlation	0.40 – 0.70
Strong correlation	0.70 – 0.90
Very strong correlation	> 0.90

*Partial correlation coefficient (PCC)*

Partial correlation is a procedure which allows the determination of the hypothetical correlation of two variables cleaned of the effect of other variables. Partial correlation is useful to identify suppressor variables. Suppressor variables reduce a larger correlation between two variables. For a three variable example ( $X, Y, Z$ ) the partial correlation coefficient  $r_{XY \cdot Z}$  between  $X$  and  $Y$  cleaned of the effect of  $Z$  is calculated as in (11). For an example of its application see section 3.5.1 Tool selection.

However, the more system knowledge that is available, the smaller the total prediction error if the modeling uncertainty is reduced with higher resolution tools, see Figure 3.8 (Trcka, 2008). The relationship between prediction error and appropriate model complexity is also discussed by Doherty (2003) in the environmental sciences.

### 3.5.1 Tool selection

$$r_{XY.Z} = \frac{r_{XY} - (r_{XZ})(r_{YZ})}{\sqrt{1 - r_{XZ}^2} * \sqrt{1 - r_{YZ}^2}} \quad (11)$$

### Regression analysis

Linear regression is a computational procedure which aims at defining the line of “best fit” for multivariate data sets. Assuming statistical significance of the measures of correlation  $r$  and  $r^2$ , the regression line can serve as a basis for rational predictions. The stronger the observed correlation between the variables, the more closely the actual value of  $Y_i$  will approximate their predicted values.

The difference between actual and predicted values of  $Y$  can be expressed as the standard error. The criterion for “best fit” is the sum of squared vertical distances between the scores and regression line. The characteristics of the regression line are the intersection with the Y-axis  $c$  and its slope  $\beta$ . For the case of one independent and one dependent variable see (12):

$$y_i = c + \beta x_i \pm SE \quad (12)$$

The slope  $\beta$  is calculated by dividing the observed covariance  $SC_{XY}$  with the variance of  $X$ ,  $SS_x$ , see (13).

$$\beta = \frac{SC_{XY}}{SS_x} \quad (13)$$

The intercept with the Y-axis is calculated as indicated in (14):

$$c = \mu_Y - \beta \mu_X \quad (14)$$

### Significance testing

The risk that statistics such as correlation or regression coefficients occur by coincidence can be excluded if when tested they prove to be statistically significant. One of the common techniques to test significance of correlation and regression coefficients is the t-test.

A *correlation coefficient* is significant if the Null-hypothesis can be rejected. The probability of the t-statistic indicates whether the observed correlation coefficient occurred by chance. Differently phrased, it indicates if the correlation is significantly different than zero. If that is the case, it can be assumed that the two variables are correlated. The critical value for the t-statistics can be read off tables. It is a function of the required probability  $p$  and degrees of freedom  $df$  (Friel, 2010).

$$t = \frac{r\sqrt{n-2}}{\sqrt{1-r^2}}; df = (n-2) \quad (15)$$

In regression analysis significance of the regression slope  $\beta$  is tested using the t-statistic, and the significance of the regression model by the F-ratio. The F-ratio tests the null hypothesis that all of the regression coefficients in the model are equal to zero. It is the ratio of the mean regression sum of squares divided by the mean error sum of squares. The probability of F is the probability that the null hypothesis for the full model is true, e.g., all regression coefficients are zero. A low probability indicates a good data fitting potential of the regression model.

### Step wise regression

To ensure the predictive quality of a regression model with the least number of model parameters, stepwise regression analyses can be applied. The technique constructs regression models in steps, adding model parameters one at the time depending on their influence on the model output, expressed by the coefficient of determination  $r^2$ . First, a regression model is constructed with the most influential parameters as determined based on values for  $r^2$  containing only single variables. Thereafter, a model is constructed with the most influential parameter and the next most influential parameter based on  $r^2$  values. The process is continued until no more model parameters with an identifiable effect on the output can be identified. Parameter sensitivity is indicated by the order in which variables are added to the regression model and their impact on the cumulative value of  $r^2$ . The process can be run using forward or backward parameter elimination. Backward elimination means excluding the parameters from the regression model one by one starting with the one having the least impact on  $r^2$ .



One typically used criterion to stop the process is based on the Pareto rule, whereby the aim is to identify the 20% of the parameters accounting for 80% of the impact. Please refer to section 5.3.7 for an example application.

### 3.3.5 Discussion of the techniques

The above sections present three techniques; differential sensitivity analysis (DSA), Morris method (MM) and Latin hypercube sampling combined with regression analysis (LHS+RA) for uncertainty and sensitivity analysis.

To allow an assessment as to which is most suitable to facilitate uncertainty propagation and sensitivity analysis for performance predictions with building simulation tools, they are judged against defined criteria.

The criteria defined in section 3.2 Applied sensitivity analysis and uncertainty propagation, are: (1) ability to cope with scale and shape input parameters, (2) capacity to account for simultaneous variation of parameters, (3) Model independency, (4) ability to treat grouped factors, (5) Useful input for decision making.

#### *Ability to cope with scale and shape of input parameters*

From the three techniques the DSA is the least able to cope with scale and shape of the parameter probability distribution function (pdf). Whilst the scale can be represented by using min and max values, the representation of the shape of the pdf requires more data points. Both MM and LHS+RA allow the representation of scale and shape of parameter pdf's.

#### *Capacity to account for simultaneous variations of parameter values*

The capacity for simultaneous parameter variations is only fully accounted for with LHS+RA. DSA and MM only vary one parameter at a time.

#### *Model independency*

The only technique that works fully independently of assumptions regarding parameter interaction, linearity and monotonicity is the method of Morris. The use of LHS+RA is conditional on the coefficient of determination  $r^2$ . If  $r^2$  is small, the explanatory capacity of the regression line is also small and the prediction error high.

#### *Ability to treat grouped parameters*

The Morris method and LHS+RA allow discrete variables to be considered as placeholders for aggregated parameters. Parameter aggregation is of little practical use for DSA.

*Provision of useful input for decision making*

All three techniques have the potential to provide input for decision making as long as estimating the combined influence of the input parameters on the output is not required. That feature in combination with the capacity to use the regression line for performance predictions at no extra cost makes it particularly attractive to use.

Taking the criteria into account, the most promising technique for uncertainty propagation and sensitivity analysis is the Latin hypercube sampling with regression analysis. Its main advantages are:

- Number of model evaluations is independent of number of analyzed parameters.
- Scale and shape of input parameter can be fully represented.
- All parameters can be varied simultaneously to provide a measure of overall output uncertainty.
- Grouped parameters can be considered for analysis.
- The technique has the potential to provide a basis for making design decisions and performance predictions.

**3.4 Prototype setup and operation**

The objective of this thesis is to support HVAC consultants by providing a measure to assess the risk of design decision and to provide valuable design guidance.

Stirling (1998) identifies some key themes in comparative risk assessment which relate to the application of uncertainty propagation and sensitivity analysis in managing the risk of performance failures.

- Make the identification of criteria and their prioritization subject to an open participative 'deliberative' process, involving all constituencies with a stake in the decision.
- Use transparent and straightforward techniques to articulate technical performance data and priority weightings on the different risk criteria.
- Focus on the construction of portfolios of less "risky technologies" or options, rather than on the highlighting of a single best option.
- Treat the risk assessment exercise as an iterative and reflexive social process rather than as a discrete analytical act.

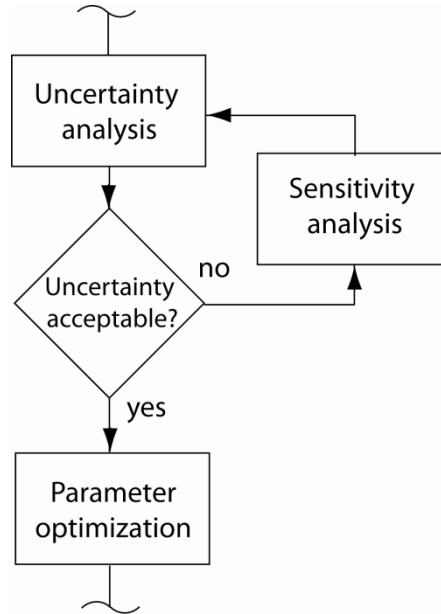
### 3.4.1 Prototype structure

With regards to structuring the analysis, an approach is suggested using techniques for uncertainty propagation and sensitivity analysis as well as global design optimization. At first uncertainty and sensitivity analysis is used. Whilst sensitivity analysis is expected to support the generation of design alternatives, uncertainty analysis provides the basis for comparison of performance and selection of design alternatives. Once the performance uncertainty is within acceptable limits global design optimization is required to fine-tune the parameter values to achieve the best possible performance. Although global design optimization is an important feature of the analysis process this thesis focuses on facilitating uncertainty propagation and sensitivity analysis and does not further elaborate on design optimization.

As an example, sensitivity analysis supports the generation of design alternatives by highlighting model parameter and/or subsystems which have a big impact on the uncertainty of performance metrics. This information enables the synthesis of design alternatives that are likely to meet the set performance requirements.

Uncertainty analysis can provide valuable input for design evaluation. If the uncertainty of a performance metric for a number of design alternatives is available, the information can be used to select the most favorable option. In the majority of cases the most favorable option represents the design alternative with the least uncertainty across the considered performance metrics.

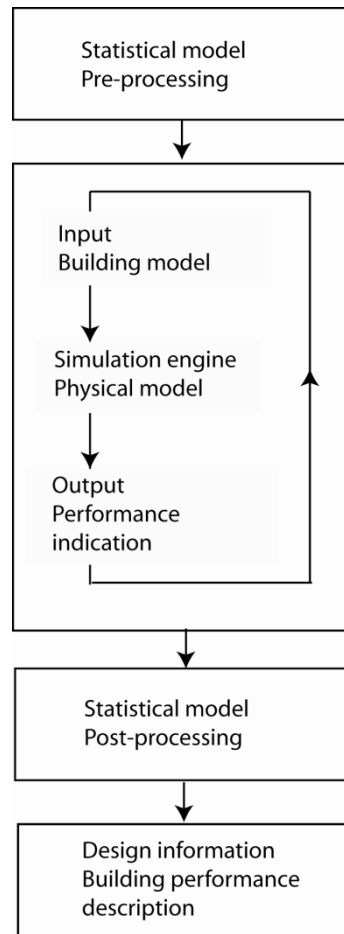
For more detail about decision support and global design optimization see Hopfe (2009).



**Figure 3.6 Process implementation:  
Uncertainty propagation, sensitivity analysis  
and optimization**

Uncertainty propagation and sensitivity analysis with Latin hypercube sampling and regression analysis requires the automation of multiple model evaluation. Furthermore, it is required to pre-process the parametric input and to post-process the simulation output. To facilitate the analysis a computational shell was built around the simulation tool, see Figure 3.7. Different to the traditional application of simulation tools, multiple simulations are conducted based on a pre-determined number of input samples.

The computational environment used for integrating the analysis was Matlab R2007a. For the parametric pre- and post-processing, Simlab 2.2 and Simlab 3.2 were used. Prototypical software extensions were implemented with different simulation tools such as LEA, IES VE and VA114 (see Appendix B – Software for more information about the tools).



**Figure 3.7 Procedure for an integration of uncertainty propagation and sensitivity analysis**

To integrate commercial simulation tools into a prototype for uncertainty propagation and sensitivity analysis, access to relevant input and output files is required. Furthermore, it eases the simulation process when the executable can be called from within the prototype. Alternatively, VBA based macros can be used to automate the process, as was the case with IES VE.

*Pre-processing*

Processing the input data involves the following three steps; (1) the definition of input parameter, (2) definition of probability density function, (3) generation of the sample matrix and simulation input files. Different to the input in state of the art tools, probability density functions are used.

They describe the parameter range and its probability of occurrence. The parameter's probability density function forms the basis for the generation of the sample matrix. Here, Latin hypercube sampling is used.

#### *Model execution*

Each generated sample represents one representation of the building model to be evaluated. The process requires that the parameter values in the building model description are replaced between the simulation runs. The number of simulation runs depends on the number of samples in the parameter matrix. To ease data access for post-processing the simulation output of interest was written into output repository, see Appendix C, Figure C.7.1 for a visual of its structure.

#### *Post-processing*

Post-processing is needed to derive the information about simulation model uncertainty and sensitivities. Information about the simulation model uncertainty can be easily extracted using statistics such as mean and standard deviation. The extraction of information regarding the sensitivity of model output to parameter variations requires correlation and regression analysis.

### **3.4.2 Verification**

Three methods are available to validate models in building simulation; comparison with analytical solutions, comparison with other models and comparison with measurements (Judkoff and Neymark, 1995). However, the focus here is not on validating the simulation model, but on verifying the operation of the extension to the simulation tool. That is achieved by comparing results obtained from the stand-alone operation of the simulation tool and results obtained using the tool extended with the feature for uncertainty and sensitivity analysis (Macdonald, 2002a). The verification procedure has to ensure that:

- the parameter values are correctly written to the simulation input file;
- the right input files are used for each model simulation;
- the results from the stand-alone simulation tool are identical to the results from the extended tool for a specific sample.

The first two points are achieved if the results from the two simulations are identical. To ensure that identical solutions are not coincidental, three samples have been tested; the first, the last and the middle sample. Whilst the verification procedure proved to be useful to identify operational inconsistencies, it also resulted in executing the stand-alone tool in command line mode to avoid the rounding conventions of interfaces. The verification procedure was executed for each individual application study.

### 3.5 Modelling complexity and predictive uncertainty

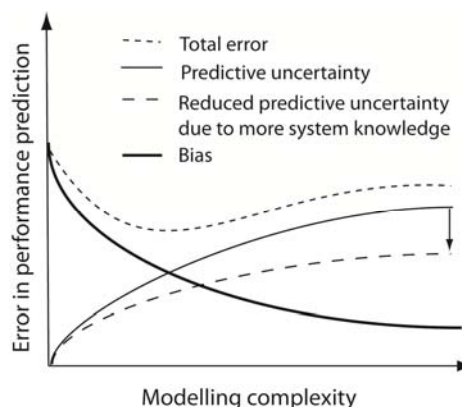
Djunaedy (2005) defined a guideline for the selection of tools to match tool resolution and problem complexity.

The governing principles are:

1. The application of a simulation tool should be problem-led as opposed to being tool-led.
2. There should be a problem-led rationale forcing the analysis from one level of resolution and complexity to the next.
3. The choice for the most favorable design alternative is to be made at the lowest level of resolution and complexity, reducing the expense for later analysis work.

Following the principles, the used tools' resolution, e.g., conceptual or detailed, should match the required modeling complexity. The analysis is to be initiated at the lowest possible level with respect to the analyzed performance metric.

An objective criterion for choosing a tool is the total prediction error as the sum of introduced bias (modeling uncertainty) and predictive uncertainty (parametric uncertainty). The predictive uncertainty increases in line with increasing modeling complexity. In the context of this thesis the modeling complexity can be related to the design stages. The author thereby assumes an increasing amount of design information with the progression from conceptual to detailed design. Concurrently to the increasing amount of design information, the building model complexity increases. The most favorable modeling complexity is the point where the total prediction error is the lowest.



**Figure 3.8 Predictive uncertainty (Doherty 2003, Trcka, 2008)**

However, the more system knowledge that is available, the smaller the total prediction error if the modeling uncertainty is reduced with higher resolution tools, see Figure 3.8 (Trcka, 2008). The relationship between prediction error and appropriate model complexity is also discussed by Doherty (2003) in the environmental sciences.

### 3.5.1 Tool selection

The feasibility to provide a consistent basis for design decisions for CDA-tools and DDA-tools is tested. The presented work is based on Struck et al. (2009b).

The test makes use of LEA as a conceptual design analysis tool and IES VE as detailed design analysis tools. The uncertainties and sensitivities of annual demand and peak loads for heating and cooling are investigated in response to varying material properties. To enable the study, both tools have been integrated into a prototypical environment. The environment facilitates:

- generation of input files from a provided sample matrix;
- execution of simulation runs, and;
- storage of simulation data for post-processing.

#### ***Assessment criteria***

The foremost assessment criterion is whether the results of the uncertainty propagation and sensitivity analysis lead to the same design decision.

Taking account of the comparative nature of the study and the absence of an immediate design problem, two criteria are proposed to inter-relate the performance of LEA and IES. The first criterion is inspired by the total prediction error.

It is argued that if the predictive uncertainty is controlled for both tools, the bias (modeling uncertainty) results in a reduced total prediction error for the detailed tool. The second criterion is inspired by the expectation that the design decision finally taken will be the same based on both sets of results.

#### ***A: Uncertainty evaluation of performance metrics***

The first criterion is based on the assumption that due to the limited extent of parametric detail available, a design proposal during the conceptual design performs with less certainty than during the detailed design stage. Following this assumption, the LEA prototype performance can be assessed as adequate when the total prediction error of the considered performance metric is equal to or larger than calculated by the IES prototype.



*B: Impact evaluation of input parameters on sensitivity of performance metric*

Partial correlation coefficients are used to assess the impact of selected parameters of the building fabric on selected performance metrics. The CDA-tool is expected to perform adequately when the sensitivities calculated in response to specification parameter variations match qualitatively the performance metric sensitivities calculated with the DDA-tool.

**Approach**

The criteria defined require studying uncertainties and sensitivities of the model output in response to changes in the model input, see Appendix B, Table B.7.1. To define an equal basis for starting the comparative analysis both tools were bestest-ed. The BESTEST procedure allows an inter-software performance evaluation for a number of predefined cases by defining performance limits.

The building model used for the tool performance analysis was the BESTEST case 600 (Judkoff and Neymark, 1995). The bestest-ing shows that IES VE complies for annual heating and cooling demand and peak loads with the BESTEST, whilst LEA under-estimates the annual energy demand for heating, see Appendix B, Figure B.7.1. The consideration of diagnostic cases is beyond the scope of the study. It was concluded that complying with three out of four performance metrics is sufficiently accurate.

Latin hypercube sampling is used to generate 200 input samples. Each sample is simulated. From the model output the overall uncertainties are analyzed using the absolute and normalized values. The sensitivities are considered using the linear partial correlation coefficient (PCC).

**Parameter aggregation**

Model simplification was accounted for by aggregating input parameter. Parameter aggregation is one technique to reduce the input requirements for CDA – tools. Whilst IES allows the definition of materials using properties such as specific heat capacity ( $c_p$ ), density ( $\delta$ ) and conductivity ( $\lambda$ ), LEA only allows the definition of one aggregated parameter, thermal resistance ( $R_k$ ), which describes the heat conduction through building elements. To facilitate an uncertainty analysis, the standard deviations of the individual properties had to be equally aggregated. Appendix B, Table B.7.2 shows the aggregated thermal resistance and standard deviation.

**Discussion of uncertainties and sensitivities**

*A: Uncertainty evaluation of performance metrics*

Three of four performance metrics show a greater uncertainty for the conceptual design analysis tool, LEA, confirming the hypothesis that a higher degree of abstraction leads to a greater uncertainty; see Table 3.4.

The peak cooling load shows a significantly lower uncertainty for LEA, in contradiction to the hypothesis.

**Table 3.4 Relative standard deviations for performance metrics**

Tool	Annual Heating Demand	Annual Cooling Demand	Peak Heating Load	Peak Cooling Load
LEA	0.353	0.099	0.178	0.011
IES	0.227	0.080	0.156	0.026

**Note:** The highlighted parameter in table 4 indicates non-compliance with the global uncertainty evaluation criteria.

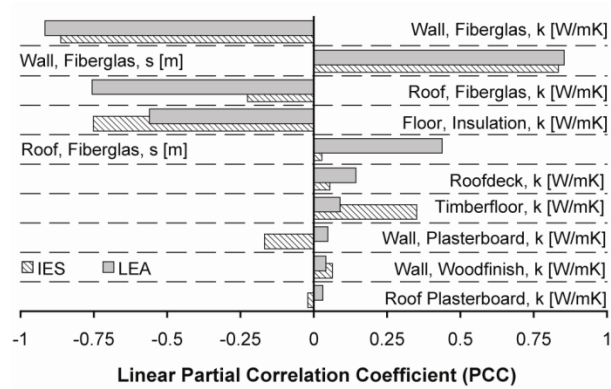
The dimensionless relative standard deviation ( $c_v$ ), also called coefficient of variation, is used to compare the uncertainties. It is the ratio of standard deviation ( $\sigma$ ) and mean value ( $\mu$ ), see (16).

$$c_v = \frac{\sigma}{\mu} \quad (16)$$

*B: Impact evaluation of input parameters on sensitivity of performance metric*

Once the uncertainties of the performance metrics have been established, the interest focuses on identifying measures to minimize the uncertainty range. It is therefore necessary to differentiate between high and low impact input parameters. Based on (Lomas and Eppel, 1992), the linear partial correlation coefficient (PCC) has been chosen as the sensitivity measure. Figure 3.9 shows the results for the peak cooling load.

A large PCC indicates a high sensitivity, whereas a small PCC indicates insensitivity. The bars have been ordered following the ranking of the CDA-tool. The top bar identifies the most sensitive and relevant input parameter and the bottom bar shows the least sensitive and relevant parameter. The algebraic sign of the PCC indicates the direction of parameter impact, which can be positive or negative. The PCC's calculated with the DDA-tool are arranged using the parameter ranking of the CDA-tool. The resulting ranking is therefore not strictly descending, but enables a direct comparison of the parameter specific PCC between the tools. The PCC based sensitivities for the peak cooling load show the least similarities between the two tools for the four metrics, see Appendix B for Figure B.7.2, Figure B.7.3 and Figure B.7.4. The top five ranks were occupied by the same parameters in changing order for peak heating load and annual heating and cooling demand. In the case of the peak cooling load, different parameters occupy the top five ranks.



**Figure 3.9 Peak Cooling Load, PCC based sensitivities, Comparison IES and LEA**  
*k= thermal resistance in W/mK; s= thickness in m*

The parameter sensitivity ranking for the five relevant parameters is shown in Table 3.5. It can be noticed that IES shows a different ranking than LEA.

**Table 3.5 Peak cooling load, Top 5 ranking parameters for LEA and IES**  
**VE**

Input parameter	Ranking	
	LEA	IES
Wall, Fiberglas, k	1	1
Wall, Fiberglas, s	2	2
Floor, Insulation, k	3	4
Timber floor, k	4	7
Roof, Fiberglas, s	5	3

Whilst both show the same ranking for the same two most relevant parameters, the following parameters are ranked differently. It is interesting that IES ranks the timber floor conductivity seventh, whilst LEA results rank the parameter fourth. Furthermore, it is surprising that IES ranks the roof insulation thickness fifth, whilst LEA ranks it ninth. Reversed sensitivities can be noticed for the conductivities of the wall plasterboard and roof plasterboard.

**Conclusions**

The case specific input parameter aggregation did not hinder the analysis of their impact on the output parameter.

The differences noticed in uncertainties and sensitivities between simplified and detailed tools can be attributed to the limited detail of the model underlying the simplified tool. However, no detailed analysis and comparison of the simulation models is possible as the tools are commercial tools with their models only briefly described in related literature.

It was found that in one instance, for the peak cooling load, the calculated uncertainty was smaller for the simplified analysis tool than observed for the detailed analysis tool. The parameter sensitivities do agree well for the heating related performance metrics but very little for cooling related performance metrics.

The differences in results lead to the conclusion that it cannot be stated with confidence that the design decision taken based on results from the simplified tools will be the same as taken based on the detailed design tool.

Consequently, it can be stated that the type of adaptation chosen to facilitate early tool use, e.g., detailed tools with simplified interfaces versus abstracted models with corresponding interfaces, does have an influence on the quality of the results when used for uncertainty propagation and sensitivity analysis. The results indicate that when using uncertainty propagation and sensitivity analysis to enhance early tool use, detailed tools with simplified interfaces present a promising way forward.

### **3.6 Concluding remarks**

The aim of chapter three was to identify and evaluate means for facilitating uncertainty propagation and sensitivity analysis to support practitioners in generating and evaluating design alternatives. To achieve this objective the concepts of risk and uncertainty were reviewed. A literature survey and individual simulation studies were undertaken to identify and test potentially promising techniques for uncertainty propagation. Finally, a prototype was developed and used to test the feasibility of using conceptual design analysis tools and detailed design analysis tools for design support.

It can be concluded that the concept of model based probabilistic uncertainty can be used to assess the risk of performance failure in conceptual design. A precondition for the application of uncertainty propagation and sensitivity analysis is the availability of data that describe the likelihood of occurrence of model parameters. If probabilistic data is not available, the use of scenario analysis is recommended to explore the performance of the building model.

The literature review of approaches for the propagation of uncertainties and sensitivity analysis concluded that external sampling based procedures are feasible to circumvent the restricted access to commercial codes. From those approaches Latin Hypercube sampling coupled with regression analysis has the biggest potential as it:

- concurrently provides measures of output uncertainty and sensitivity,
- accounts for simultaneous variation of model parameters,

- treats grouped parameters, representing subsystems and components, and
- provides useful input for decision making.

Taking into account the characteristics of the analysis, a prototype was formulated which acts as a shell extending commercial tools with a statistical pre- and post-processor. Multiple simulation runs are automatically executed and the results are stored in an output repository.

The prototype was subsequently used to facilitate uncertainty and sensitivity analyses of a simple one zone case study, with two different tools. One was a conceptual design analysis tool and the other a detailed design analysis tool. It was found that the results differ, conveying limited confidence in drawing the same design decision from both sets of results. Based on the results of the tool evaluation, detailed design analysis tools, with potentially adaptable interfaces, are recommended for use in supporting the conceptual design stage.

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# 4

## Parametric input for uncertainty propagation

Whereas the previous Chapter was dedicated to the identification of a suitable method and the development of a computational prototype to facilitate uncertainty propagation and sensitivity analysis, the focus of the current chapter is on the character and availability of the parametric input for the analysis.

Current simulation tools' input dialogues are restricted to accept one value for each model parameter. However, probabilistic approaches require the definition of a parameter range, plus information about its probability density function. The main research question addressed in Chapter 3 is:

How to represent probabilistic parameter uncertainties in the developed computational prototype?

The focus is thereby on scenario and specification uncertainties. The questions which arise specifically for the use of the prototype are:

1. What are the requirements for the data format so that it can be used with the favored Latin hypercube sampling and regression analysis?
2. What uncertainty data for scenario and specification uncertainties are available?

The introductory section of chapter 4 gives the ideas behind the use of scenarios and indicates their advantages and disadvantages in the context of building simulation. Thereafter, part 1 presents important variables and their uncertainty range for representing occupancy patterns derived from observations and measurements in a real office environment. Part 2 is dedicated to the representation of uncertainties due to climate variations. It gives a review and the state-of-the-art of the used weather data sets worldwide and later specifically addresses The Netherlands. Finally, an approach for considering climate uncertainties with BPS-tools is proposed.

### ***Robustness assessment of design alternatives***

Observed phenomena such as the heat island effect (Crawley, 2008b, Robinson, 2011) and global warming (Pachauri and Reisinger, 2007) extend the scope of simulation studies towards assessing the robustness of design alternatives for a warmer climate than the building was designed for.

In the context of this work robustness is defined as:

*“...the integrated building systems ability to maintain defined performance requirements, even if the conditions it is exposed to deviate from design conditions”.*

For the design of integrated building systems (IBS's), practitioners expect HVAC components to function successfully for up to 30 years. There exists a risk that the IBS fails to meet its performance requirements before the end of the expected component lifetime if operational conditions differ greatly from design conditions. Experts speak about an IBS not being robust to climate variations.

There are two approaches to assess the robustness of IBS; the absolute and the relative. The absolute assessment makes use of set maximum and/or minimum performance limits. It allows the system to be judged as robust or not robust. The relative assessment considers the rate of change. The relative approach provides the means to rank-order considered design alternatives. The relative assessment has the advantage of being applicable if set performance limits are not available.

Different performance metrics to assess robustness are evaluated in this context: peak cooling load in section “Applicability of climate data sets for the robustness assessment” and annual cooling demand and adaptive temperature limits 80% in section “Robustness assessment of HVAC systems”.

The peak cooling load is relevant as it relates to the capacity of the HVAC system components. If the required peak cooling demand cannot be provided, the required thermal comfort is compromised. The annual cooling demand relates to energy use and subsequently to the long term economic viability of the building. However, as energy costs only account for ca. 6% of the total monthly expenses for an organization, their impact on decisions governing more efficient performance is expected to be limited (WBCSD, 2007). The impact of performance metrics related to thermal comfort is expected to be significant as it directly influences the productivity of building users (Wargocki, 2011, Bluysen, 2010, Struck et al., 2009c, Kosonen and Tan, 2004, Ole Fanger, 2001). In assessing the thermal comfort of design alternatives the ATL 80% criterion is used.

*Adaptive temperature limits (ATL).* The adaptive temperature limits differentiate building types into alpha and beta buildings. The differentiation is based on the degree of influence individuals can practice on their environment.

Three performance bands of different quality, which are not to be exceeded, are defined for both building types. The central band, class B, indicates an acceptance of 80% of the building occupants over the use period of the building. The inner band, class A, represents the most stringent requirement and indicates a high quality thermal environment with an acceptance of 90% of the building occupants. The outer band, class C, is the most relaxed, only representing an acceptance of 65% of the occupants. Class C is not to be applied to new buildings. Exception can be granted e.g. to historic buildings to limit the technical and financial effort for refurbishments.



The performance bands are defined by the operative temperature and a derivative of the external air temperature; the four-days running mean outdoor temperature (RMOT). The RMOT is calculated from weighted daily means of the current and the three previous days (ISSO, 2004).

#### **4.1 Specification uncertainties**

Specification uncertainties in the context of conceptual building design are **uncertainties** which arise from incomplete information about the integrated building system under consideration. The specification of the building design relates to many aspects such as building geometry and physical properties of the building material. This section focuses on the physical properties of the building fabric.

To allow the representation of heat & mass transfer phenomena in and around buildings, integrated BPS-tools require the definition of construction layers. Each layer is typically defined by material specific information such as: specific heat capacity, conductivity, density, emissivity, solar absorbance and vapor resistivity.

The uncertainty in physical material properties is caused by differences in the materials thermal on-site and laboratory performance. Variables influencing the differences are temperature, moisture content, material aging processes and quality of workmanship. The influence of the quality of workmanship on the building performance is difficult to determine as its sources can vary widely. For example poor workmanship can originate from the inappropriate use of building components or materials and/or the lack of design knowledge concerning material deterioration, poor design as well as the lack of site supervision and construction monitoring (Iwano and Mwasha, 2012). As this thesis is concerned with supporting the conceptual design stage rather than the construction phase, material aging processes and quality of workmanship are not further elaborated on.

There are three potential sources for the acquisition of material property data to represent material performance variations (1) Manufacturers catalogues, (2) Numeric derivation, and (3) Third party data collections.

##### ***Manufacturers catalogues***

Material properties are typically provided by manufacturers when introducing a product and are based on measurements. Methods recommended by EN ISO 10456:1999 to obtain data for the conductivity are guarded hot plate -, heat flow meter – or hot box, e.g., Data provided by manufacturers are typically in “Design thermal value” format (EN ISO 10456, 1999). This value represents a typical performance of the material considered, under specific external and internal conditions, when incorporated in building elements, such as walls, flooring or roof constructions. These value characteristics are not sufficient to support uncertainty propagation. Material specific design thermal values can be found in Manufacturers’ catalogues or building codes.

### ***Numeric derivation***

Methods such as those documented in EN ISO 10456:1999 exist for deriving material properties for other than fixed standardized conditions, in “Declared thermal values” format. Declared thermal values represent the expected value of a thermal property of a material derived from measured data at reference conditions. This is particularly interesting if one wants to derive performance values for the compilation of a sample matrix using standard deviations. However, the methods can rarely be used due to inadequate information on test conditions, measurement sample size and limited test documentation.

### ***Third party data collection***

The recognition of the importance of material performance values describing their real site behavior lead to research projects to collect data about material properties. One document repeatedly referenced, a milestone towards making data available for UA, is Clarke's et al (1991) report. The aim of compiling the document was to obtain data to describe variations of material properties as a function of temperature and/or moisture content. In the due course of the project 14 international datasets were collected, classified, tabulated and published. The authors identified a number of issues that limit the representativeness of the collected data, such as:

- The sources of much of the data are not documented.
- Little information is provided on experimental conditions.
- Suspicion exists that agreement between data sets can be attributed to historical borrowing.
- Quotation of values with missing reference to single or multiple measurements.

Based on the issues above it is doubtful that the data are representative for the full extent of potential variation of temperature and moisture content. Furthermore, the data available does not cover performance variations due to material aging processes. However, the tabulated data sets are the easiest to access for research in the area of uncertainty propagation and sensitivity analysis.

Standardized material property data sets are sufficient to use for steady state design calculation to demonstrate code compliance. However, their characteristics do not suffice to provide an indication of accuracy, as they do not allow the representation of parameter range and probability distribution.

**Table 4.1 Building specification data distribution  
(Corrado and Mechri, 2009)**

Parameter	Distribution
Room dimensions	Log-normal
Material properties (conductivity, density, specific heat capacity)	Normal (truncated)
External heat transfer coefficient	Weibull (monthly)

Uncertainties in physical input variables are typically normally distributed around their mean value. Efforts which give tabulated material properties and their variation are published by Clarke (1991), Lomas and Eppel (1992), Wit (2001), Macdonald (2002a) and Corrado and Mechri (2009), see Table 4.1.

### **Conclusions**

Fragmented efforts have been reported which target the provision of parametric input characterizing building specification uncertainties. To the author's best knowledge, no efforts are reported which validate the data with respect to their local representativeness, actuality and applicability. One feasible approach is conducting measurements and surveys to test the validity of the data. In section 4.2.2 Occupancy pattern, an effort is reported to test the local representativeness and applicability of occupancy design data against results from a building survey.

### **4.2 Scenario uncertainties**

This section is dedicated to the representation of scenarios under which the building is likely to operate in the future. The focus is thereby on the use pattern and climate scenarios. This is because climate and building use impose dynamic loads on the building system. In the context of this thesis the dynamics are considered an uncertainty with respect to the required building performance.

During design, the performance uncertainty is traditionally dealt with using worst case scenarios for system sizing and overheating risk assessments. However, worst case scenarios are not suitable for designing high performance buildings, e.g. zero net energy buildings, as they result in over-sized building services systems. Over-sized systems have the distinct disadvantage that they operate the majority of time in the less efficient part-load mode.

To better fit the system performance to the governing load profile, quantitative knowledge about the uncertainty of internal loads and external climate is required. By providing the knowledge practitioners are enabled to assess the risk of discomfort against load based on probabilities and confidence intervals.

The representation of uncertainties for use patterns and external climate is discussed in the following sections. Different to deterministic, stochastic processes are processes where the state of the system at a given time step does not fully determine the state of the system at the following time step (Jones et al., 2009).

In the built environment the perceived randomness of the system performance can be attributed to occupancy presence, interaction of occupants with the controlled system components and the external climate. Stochastic approaches derive the uncertainty from behavioral or global circulation models. They are, in most cases, pre-processors to building simulation models. The aim is to represent the realistic variability in behavioral preferences and external climate to predict their interaction with the building and building systems.

Studies have been published aiming at deriving models from empirical studies on subjects such as: evaluation of building space utilization (Tabak, 2009), simulation of occupancy presence (Page et al., 2008), interaction of occupants, lighting and blinds (Reinhart, 2004) and occupant influence on window openings (Haldi and Robinson, 2009). Bourgeois's (2005) work sets out to bridge the gap between energy simulation and empirical data. The self-contained simulation module, SHOCC, was applied by Hoes et al. (2009) integrating the User Simulation of Space Utilization-model (Tabak, 2009) with the ESP-r simulation program. However, a generalization of derived models is rarely possible due to the origin of the raw data. The raw data is typically obtained from controlled environments for a specific purpose.

#### **4.2.1 Deterministic scenario analysis**

Deterministic approaches are commonly scenario based. The following section reviews the use of scenarios and proposes requirements for their definition in the context of building design.

Dessai and Hulme (2003) suggest the use of scenario analysis, see chapter 3, as an appropriate method to quantify uncertainties where no probabilities are available. Scenario analysis attempts to reduce uncertainty attributed to variables of complex dynamic environments to manageable proportions. Different to probability based techniques for quantifying uncertainties; it is based on qualitative causal thinking.

The application of scenario analysis has a long history and is applied in many different disciplines, such as: environmental analysis (Dessai and Hulme, 2003), war fare (Kahn and Wiener, 1967), sociology (Ramsey and McCorduck, 1996), and business management (Schwartz, 1996). Ramsey McCorduck (1996) characterizes scenarios as follows:

*“Scenario’s don’t predict the future so much as they illuminate it, preparing us for the unexpected. Scenarios are multiple approaches to the future, stories of the inevitable and necessary (...) recombined with the unpredictable and matters of choice.*

*The best scenarios aren't necessarily those that come true, they're the ones that subvert expectations, providing deep insights into the changes happening all around us. The better scenarios are the more they penetrate to the deepest possible understanding of the present."*

The use of performance simulation during detailed design for deterministic purposes such as compliance checks requires normative scenarios, in contrast to exploratory scenarios (Godet and Roubelat, 1996). Normative scenarios are defined on the basis of the desired or feared vision of the future, such as best and worst case scenarios. Examples are the often used worst case scenarios of internal gains, and average and extreme data sets for the representation of the climate, such as test reference years (TRY) and design summer years (DSY), respectively. Exploratory scenarios start with past and present trends, leading to a likely or unlikely future, such as the KNMI'06 scenarios. Following Berkhout and Hertin (2003) they are based on four assumptions.

- The future is not a continuation of the past relationships and dynamics but is always shaped by human choice and action.
- The future cannot be foreseen; however exploration of the future can inform the decisions of the present.
- There is not only one possible future, uncertainty calls for a variety of futures mapping a "possibility space".
- The development of scenarios involves both relational analysis and subjective judgment.

Kenter (1998) based on Wack's work (Wack, 1985a, Wack, 1985b) differentiates between (1) learning scenarios and (2) decision scenarios. Similar to exploratory scenarios, learning scenarios aim at gaining insight and understanding. They have an exploratory nature and map the connections between various forces and events governing the system of concern. As the exploratory scenarios are not considered effective planning instruments, other more specific scenarios are required. Decision scenarios, comparable with normative scenarios, combine two domains; the domain of facts based on explicit knowledge and the world of perception characterized by tacit knowledge. Wack argues that decision scenarios are necessary to connect and communicate to the decision maker. In the context of conceptual building design the used occupancy profiles and climate data sets represent normative scenarios. They are based on design data and rarely demonstrate the factual variety of possibilities<sup>1</sup>. For that purpose exploratory scenarios are required. Other sources present more scenario types based on aspects such as representation, subject, quantification and time among others.

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<sup>1</sup> For the due-course of the thesis the terms exploratory and normative scenario are used.

Mietzner and Reger (2005) define the value of scenarios as:

*“...being able to take complex elements and weave them into a story which is coherent, systematic, comprehensive, and plausible.”*

Mietzner and Reger (2005) identify two distinct disadvantages of using scenarios: (1) the necessity to collect expert knowledge and judgment to define comprehensive scenarios, as well as (2) the risk of diverting to wishful thinking, considering the most likely, best- and worst-case scenarios, only. Still, the use of scenarios also has a number of advantages:

- potential to consider events with low probability but strong impact,
- the possibility of considering different futures side by side,
- potential to recognize “weak signals” for discontinuities and disruptive events,
- function as vehicle to improve strategic communication about performance.

The use of scenarios in building design practice is limited to normative scenarios. However, the robustness assessment of the future performance of design alternatives requires the provision of exploratory scenarios.

#### **4.2.2 Occupancy pattern**

During early design stages equipment is unlikely to have been specified, and in speculative developments will never be known to the design team. Uncertainty sources are typically related to knowledge of office equipment specification and use (Wilkins and Hosni, 2000, Lee et al., 2001, Lam et al., 2004a).

State of the art simulation tools typically make use of some sort of predefined schedule (Robinson, 2006) to represent occupancy presence and equipment gains. Traditionally, equipment gains were based on name plate power consumption. The name plate power consumption is, for a number of reasons, too high to be used for the design of HVAC systems (Esbensen, 1996, McNicholl and Lewis, 2001, Duska et al., 2007).

- Very few types of office equipment have a peak power consumption that approaches the name plate power.
- Many types of equipment have a peak power consumption when working and a much lower consumption when idle, known as variable load machines, e.g., copy machines, scanners, vending machines.
- Many types of equipment such as PCs have capabilities to switch to “sleeping mode” with low power consumption.
- The entity of installed equipment is rarely used at the same time.

The most advanced form to represent occupancy presence and internal gains is the use of diversity profiles. Diversity profiles make use of factors between 0 and 1, which are used as multipliers for operator defined maximum loads. Variability is introduced by defining diversity factors or 24h-profiles to different day types (Abushakra et al., 2001, Bourgeois et al., 2006).

The use of diversity profiles has at least two key advantages: (1) They represent more realistic load profiles than using static peak load design data, and (2) they allow the definition of a great number of scenarios in addition to the worst case scenario.

However, the application of any such data set also has a number of shortcomings. So are the diversity profiles specific for a *work place culture* (e.g., working hours), *building structure* (e.g., exposure and response to external loads), and *system sensitivity to short term occupancy variation* (e.g., manual vs. automatic controlled lighting). Whilst their application might be suitable for the prediction of annual energy and peak loads, the annual averaged data sets are expected to be less suitable for the assessment of thermal comfort due to adaptive clothing.

The fragmented efforts to generate stochastic models for the simulation of interaction between occupants and systems led to the decision to use scenario based diversity profiles for uncertainty quantification. A literature review revealed probability distributions to represent the parameter uncertainties, see Table 4.2.

**Table 4.2 Building use data distribution (Macdonald, 2002a)**

Parameter	Number of items	Distribution
Occupants, heat gains	One	Uniform
	Small group (<10)	Triangular
	Large group	Normal
Equipment, heat gains	One	Uniform
	More	Triangular
	Many	Normal
Use period, equipment		Log-normal <sup>1</sup>

<sup>1</sup> from Corrado and Mechri (2009)

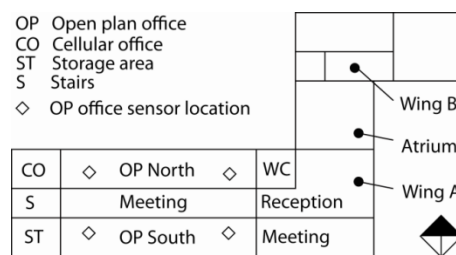
Whereas knowledge about parameter distributions is available, little is known about the local representativeness of data with respect to internal gains in operating offices (Hand et al., 2008). That is why an effort was made to collect data for an office building characterized by the local work place culture, system use and climate.

The following issues were addressed:

1. Local representativeness of published data: How good represent published data internal gains and electricity use in an operating office?
2. Load dominance: Which occupancy related load dominates the electricity demand for the surveyed office?
3. Diversity profiles: How divers are the local load and occupancy profiles?

**Survey of office occupancy and equipment gains**

Data was collected by repetitive walkthrough-surveys and meter readings in May 2009 in an office building located in Amsterdam. The “BETA-building” is a four-story high office building with two wings, A and B, connected by an atrium, see Figure 4.1. For more detailed information about the surveyed building, see Appendix D - “BETA-Building” description.



**Figure 4.1 “BETA-building”, 4th floor - plan view**

The aim was to collect data to address issues as (1) data representativeness, (2) load dominance and (3) diversity profiles.

The levels of occupancy, in-use lighting and electrical equipment were surveyed once every hour on four days, Friday 8<sup>th</sup>, Tuesday 12<sup>th</sup>, Thursday 14<sup>th</sup> and Monday 18<sup>th</sup> of May, 2009. The equipment type, its numbers, and where available name plate ratios were recorded. Missing data was taken from manufacturers’ catalogues and relevant publications.

The following observations were made concerning occupancy pattern and equipment use:

- The office use period differs significantly from the official working hours, 8:30-17:30. People were present from 7:00 till 20:00 on the four survey days. The access lock of the of the Wing A office unit also shows people present on at least one day in five of six weekends.
- Office lighting was always “On” during occupation. Lighting was switched “On” by the person arriving first and switched “Off” by the person leaving last.



- A fraction of electrical equipment was running overnight, which accounts for 10% of the electrical equipment gains present during office occupation.

From the data, load profiles were compiled. The profiles were averaged and integrated to estimate the electricity use over the considered period. The electricity use data from the meter reading and estimation was compared to validate the load profiles. The comparison shows a deviation of 8%; see Table 4.3. The acceptable deviation is likely to be caused by the weekend use of the office.

**Table 4.3 Estimation of electricity consumption for office unit in Wing A, Floor 4**

Consumer	Recorded power consumption [W/m <sup>2</sup> ]	Subtotal [kWh]	Percent on surveyed total [%]
Lighting	11.5	3129	44
Electrical equipment	6.7	1812	26
Fan coils <sup>3</sup>	4725W	990	14
Server + Split unit	1800W	693	10
Electrical equipment, other <sup>2</sup>	0.7	238	3
Lighting, other <sup>1</sup>	8	166	2
Walk-through survey		7028	100
Meter reading		7585	/

The data presented are averaged data from the four surveyed daily data sets. The gross floor area of Wing A floor 4 is 920m<sup>2</sup>, and the net floor area is 837m<sup>2</sup>.

<sup>1</sup> Circulation spaces and toilets.  
<sup>2</sup> Communication equipment (telephones, fax, television.)  
<sup>3</sup> 29 Fan coil units at 105W.

The biggest proportion of the electricity use can be attributed to the office lighting (44%) followed by the electrical equipment (26%), fan coils (14%), and server (10%).

To identify whether published data are representative of the office use, the diversity profiles and specify loads are compared with published data, see Table 4.4.

The gains surveyed for people and electrical equipment are at the lower end of the scale compared to published design reference data. The lighting gains are  $16\text{W/m}^2$ , well above the  $10\text{W/m}^2$  by ISSO (1994) and  $13\text{W/m}^2$  by EN15232 (2007). They lie between the min. and max. values published by Knight and Dunn (2003).

**Table 4.4 Internal gains comparison**

	People	Light	Small power	Total
Unit	$[\text{W/m}^2]$	$[\text{W/m}^2]$	$[\text{W/m}^2]$	$[\text{W/m}^2]$
<b>Design guidance</b>				
ISSO300	8-10 <sup>3</sup>	10	2-35 <sup>3</sup>	20-55 <sup>3</sup>
EN15232	7 <sup>5</sup>	13	10	30
<b>Surveys</b>				
Knight <sup>1</sup>	20	8-32 <sup>3</sup>	7-45 <sup>3</sup>	37-90 <sup>3</sup>
Knight <sup>2</sup>	6-30 <sup>3</sup>	6-34 <sup>3</sup>	6-34 <sup>3</sup>	21-86 <sup>3</sup>
Offices survey <sup>4</sup>	5	16	10	32
Wing A survey <sup>4</sup>	3	8	6	17

<sup>1</sup> Composite guidance.

<sup>2</sup> Calculated values based on walkthrough survey.

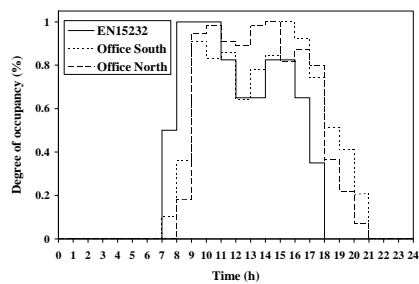
<sup>3</sup> Minimum and maximum values.

<sup>4</sup> Average from official working hours 8:30-17:30.

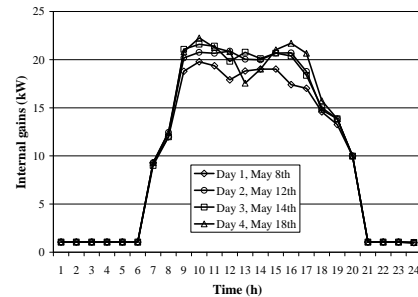
<sup>5</sup> From EN15232 (2007), based on  $13.3\text{m}^2/\text{person}$  and  $86\text{W/P}$  sensible gains

Considering all occupied spaces of Wing A, across all four-stories, reduces the specific gains to  $17\text{W/m}^2$ , corresponding to 54% of the gains recorded in the office spaces during the walkthrough survey.

The average occupancy profile for the office was compared with the profile published in EN15232:2007, see Figure 4.2. The data indicates a one hour shift to the right. It also shows approx. 20% more occupants present in the afternoon compared to EN15232, and approx. 30% of the occupants being present two extra hours in the evening. The employees of the observed office start working an hour later in the morning and work late in the evening. Wilkins and Hosni (2011) state that it is now realistic to design office spaces with peak equipment loads of  $2.7\text{W/m}^2$ .



**Figure 4.2 Diversity profile for office occupancy for, Comparison of EN15232 and observations, Beta-Building, Floor 4, Wing A**



**Figure 4.3 Observed cumulative gain profiles**

Figure 4.3 shows a comparison of the cumulative profiles from the survey spaces on the 4<sup>th</sup> floor of the Beta-building. Survey day 1 represents the set with the lowest gains and day 4 the set with the highest.

### Survey results

The survey results suggest that the design guides consulted still provide feasible data. However, it has to be acknowledged that the design should be based on the lower end of the provided scale. It was found that the specific gains by people and electrical equipment are at the lower end of the scale, whilst the gains by artificial lighting are medium to high. The cooling demand for the office would be overestimated using ISO 300 medium high internal loads for Dutch office buildings for the period considered.

The empirical data confirms the trend towards decreasing equipment gains and proportionally increasing gains by lighting. For the office of concern the office lighting dominates the electricity use with 44% of the total usage. Subsequently, it also shows the highest specific gains with 16W/m<sup>2</sup>.

The observed occupancy profiles don't show significant deviation among them. However, they deviate from the standardized profiles, indicating the influence of the workplace culture. The occupancy profiles for the office spaces show similar trends to published data but indicate a higher people presence in the afternoon and an average of two extra working hours.

### 4.2.3 Climate data

This section considers the character and use of climate data in building simulation specifically for the robustness assessment of integrated building systems (IBS's). The investigation is dedicated to data used in The Netherlands.

Still, the review of data formats and methods for compiling weather data sets for BPS cover international initiatives.

Weather variations occur in different temporal scales, e.g., daily, seasonally, annually, decadal. The term “weather data” describes measured data representing historic weather events for a specific location. “Climate data” are different as they refer to data sets that are considered representative for larger spatial and temporal scales. An example of a climate data set is the test reference year for energy prediction for the Netherlands. The annual set was compiled from long term measured data for the location De Bilt. From the measured data, based on statistics, months were selected to form a climate year representative for the Netherlands.

Traditionally, BPS tools use annual data sets containing series of mean hourly values for variables, such as dry-bulb temperature, relative humidity, solar radiation and wind speed and direction. These files are typically based on historical data and are used as reference. Clarke (2001) states:

*“...a reference data set is a weather data collection which is representative, when judged against relevant criteria”.*

The data set can reference average, most-likely or extreme weather conditions for a specific location. For that purpose different file types are in use such as the Typical Metrological Year (TMY), Test Reference Year (TRY) or Design Summer Year (DSY). The type of file is chosen specifically for the required analysis.

Common simulation applications are energy analysis and compliance testing, equipment sizing and engineering studies (Hensen and Lamberts, 2011). Another application of performance simulation is the robustness assessment of design alternatives (Clarke, 2001).

### ***Future climate data***

Data sets generated based on historic weather data are unlikely to satisfactorily describe the external future climate conditions because they cannot account for global warming or cooling and heat island effect to be experienced in the future. To represent climate change in data sets for performance simulation, Guan (2009) differentiates four methods: (1) Statistical extrapolation (Degree-day method); (2) Use of global climate models. (3) Imposed offset method; and (4) Application of stochastic weather models.

Of those four methods, the latter two are extensively used in research on building simulation and performance predictions the application of stochastic weather models by e.g., Wilde and Tian (2011) and Kershaw (2011) and the imposed offset method by e.g., Belcher et al. (2005) Crawley (2007), Degelman (2002), Guan et al. (2005).

### *Stochastic weather models*

A number of independent studies accounting for the stochastic nature of the climate exist. See Adelard et al. (2000) for an overview. One of the latest developments is the introduction of the UK weather generator for future daily climate projections (UKCP09) by Jones et al. (2009). The weather generator (WG) provides projected synthetic time series based on the output of a stochastic model for rainfall as primary variable.

Other variables are generated based on information about inter-variable relationships. The outputs of the generator are variables such as: daily mean temperature, daily temperature range, vapor pressure and sunshine duration. The process involves stages A to D:

- A. Calculation of descriptive statistics for baseline climate (1961-1990).
- B. Identification of change factors (monthly time scale) for a specific location and required climate change scenario.
- C. Refitting the stochastic rainfall model for perturbed future daily rainfall statistics.
- D. Generation of other weather variables based on perturbed rainfall series using observed inter-variable relationships.

In a next step the output variables are processed to calculate potential evapotranspiration (PET), daily minimum and maximum temperature, relative humidity as well as direct and diffuse radiation. Subsequently, the WG provides the possibility to disaggregate the daily values to hourly values by using the observational data. The process results in a number of annual climate data sets. It is suggested to generate at least 100 data sets to ensure that the full variability is accounted for.

### *Simulation process*

The output from the described process requires the simulation of each climate file individually. Data sets representing possible futures can be represented as discrete variables and used for the sampling process.

### *Imposed offset method*

The imposed offset approach is widely used and merges projected climate change data with historic data sets (Jentsch et al., 2008); (Belcher et al., 2005); (Crawley, 2008a). It makes use of three operations; shifting, linear stretching, and shifting and stretching. The projected change is imposed on the parameter external air temperature. Its probability density function is either shifted, stretched or shifted and stretched.

### **Data sets for the Netherlands**

Until 2008 two data sets were used for performance predictions in the Netherlands; one for overheating risk assessment “De Bilt 64/65” and one for the calculation of the annual energy demand the “Test Reference Year”.

The “De Bilt 64/65” data set, recorded data from the period April 1964 to March 1965, was regarded as an ‘average’ summer (ISSO, 2004). Weele (2005), as well as Schijndel and Zeiler (2006), respectively indicated a limited representativeness of the data set for climate change.

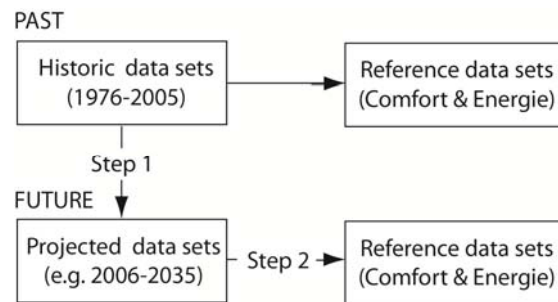
The “Test Reference Year” (TRY) data set is based on the period 1971-1980 and was available for energy calculations. It also formed the basis for the Dutch Energy Performance Standard calculations.

To support the robustness assessment of integrated building systems to climate change appropriate climate files are required. A two-step procedure was used to generate the files, see Figure 4.4.

Step 1: Projection of periodic data sets into the future.

Step 2: Derivation of annual reference data sets.

To accomplish the first step Dutch climate change scenarios and the KNMI data transformation was used. Step 2 required the application of the procedures as outlined in NEN 5060:2008.



**Figure 4.4 Two-stepped procedure for generating projected climate data sets**

The following three paragraphs describe the input to the above procedure, the Dutch climate change scenarios and KNMI data transformer, as well as the standard NEN 5060 outlining the methods to generate the reference data sets.

### *Dutch climate change scenarios*

The Intergovernmental Panel on Climate Change (IPCC) has formulated a common set of climate change scenarios based on assumptions about the likely future development of energy demand, emissions of greenhouse gases, land use change and future behavior of the climate system. The scenarios are based on results of Global Circulation Models (GCM). GCMs are numerical models for the simulation of physical processes in the atmosphere, ocean, cryosphere and land surface. The models describe the climate using a three dimensional grid with a typical horizontal resolution of 250-600km.

Nested regional circulation models (RCM) are used to down-scale the climate change scenarios. Based on input of GCMs and RCMs, the Royal Dutch Meteorological Institute (KNMI) defined four likely climate change scenarios based on two observed phenomena: the global temperature increase and the change in airflow pattern over Western Europe.

With respect to the temperature increase, the KNMI distinguishes between a global temperature rise of 1°C and 2°C for the period 1990 till 2050. With respect to air flow pattern, the temperature increase scenarios are associated with more westerly winds during winter and more easterly winds during summer, see Table 4.5.

**Table 4.5. Values for steering parameters to identify climate change scenarios (Hurk et al., 2006)**

Scenario	Global temperature increase in 2050	Change in atmospheric circulation
G	+1°C	Weak
G+	+1°C	Strong
W	+2°C	Weak
W+	+2°C	Strong

With the current knowledge it is not possible to indicate which of the four scenarios is most likely. All four are plausible and are therefore regarded with equal probability for performance simulations.

### *KNMI'06 Climate scenario data transformation*

The KNMI website (KNMI, 2011) provides the possibility to transform historic datasets for temperature and precipitation into projected future data sets for a specific location and temporal horizon. The transformation is based on three steps, taking into account the different changes in extremes and mean values over a given period.

Step1: Based on daily means of the standardized historic period the tool calculates the median 10th and 90th percentile for each month of the historic data set.

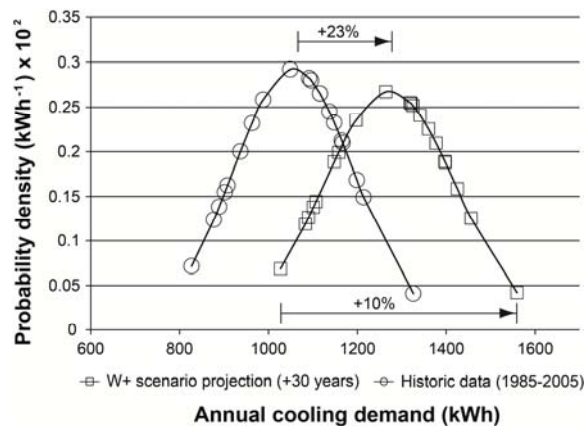
Step2: The tool determines the deviation of the future climate scenario for the specific time horizon from the historic dataset. The deviation is hardcoded for the horizons 2050 and 2100. Linear interpolation is used for other horizons.

Step3: The historic data series are transformed using the established deviation.

The extent of weather variables for which future change projections are available differs as to which resource is used. The Royal Metrological Institute of the Netherlands (KNMI) publishes dry bulb temperature and precipitation projections for four different climate change scenarios and time horizons.

The difference between the projected daily mean air temperature and measured historic daily mean air temperatures was added to each hour of the corresponding day. By repeating the procedure, 20 projected data sets were created for the use with simulation tools. The work was accomplished in close cooperation between VABI BV and the TU/e.

The impact of the climate projections on the performance of an office space is visualized in Figure 4.5. The office space is a 3.6x5.4m intermediate office with one external wall facing south, equipped with 4-pipe fan coil unit and medium internal gains.



**Figure 4.5 Probability distributions of the annual cooling demand for a cellular office exposed to historic and projected climate data.**

The probability density distribution of the annual cooling demand for the historic and projected climate data is indicated.



Two issues can be observed. Firstly, the distribution mean for the projected data is about 23% higher. Secondly, the uncertainty of the projected data increases by about 10%.

#### *NEN 5060:2008*

At the beginning of 2008 the NEN 5060:2008 was released. The new national standard presented updated reference weather data sets for energy calculations and overheating risk assessment. It is based on 20 years of historical weather data (1986-2005) for the weather station De Bilt. Statistics are used to select 12 months, together forming the reference years. The new standard implemented the statistical procedure for compiling a data set for energy predication and calculation of the energy performance coefficient (EPC) as published in the NEN-EN-ISO 15927 part 4.

For the first time a method was outlined for the generation of synthetic climate data sets for thermal comfort risk assessment. The three reference years 1%, 2% and 5% represent the risk of exceeding and undercutting air temperatures experienced during the reference period. The procedure is based on part 2 and 5 of NEN-EN-ISO 15927.

A frequency distribution of '5-day-average' temperatures is generated. Based upon the distribution, months are selected with a probability of 5%, 2% and 1% for the occurrence of a warmer summer and cooler winter. The five day mean temperature was chosen according to the time constant of buildings complying with the 2003 Dutch Building Regulations (Bouwbesluit 2003).

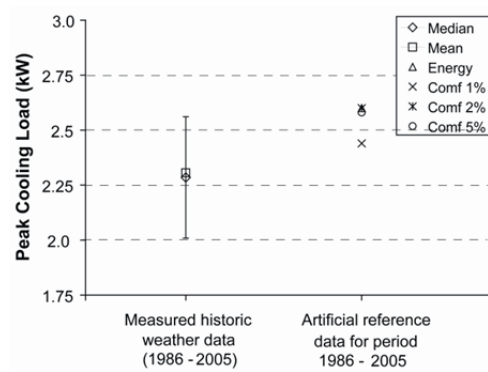
The data originate from a 20 year reference period, 1986 – 2005. The files are named 1%, 2% and 5%, corresponding to the risk of the five day mean temperature being exceeded for 1%, 2% or 5% in summer and being undercut for 1%, 2% or 5% in winter. The 1% year is the most extreme year as the risk that the external temperature during the reference period exceeds or undercuts the temperature of the reference year is only 1%. Corresponding to the above, the 5% year represents the most moderate of the three files. The selected months are joined to form a reference year. The reference years are revised every 5 years and updated when necessary.

#### *Future projected and reference data sets for the Netherlands*

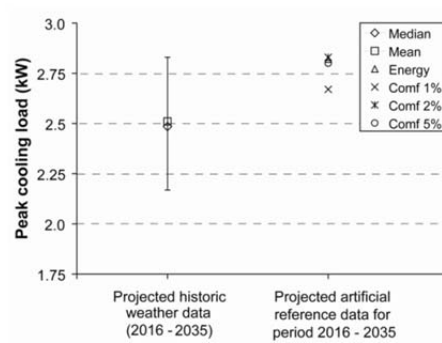
The historic data sets were projected 30 years into the future, 2006 – 2035, using the most extreme KNMI climate change scenario, W+, see Figure 4.4. The 30- year time horizon was chosen as this period corresponds to the expected lifetime of HVAC equipment. Using the projected data sets as outlined above, four artificial reference data sets were generated by selecting the corresponding months as defined in the NEN 5060. The four artificial reference data sets, one for energy and three for thermal comfort assessment, represent the 30-year projected reference period 1986 - 2005.

**Applicability of climate data sets for the robustness assessment**

Prior to using the artificial reference data sets to investigate the robustness of integrated building systems (IBS), the data was tested. The aim was to test how useful published reference data sets are compared to measured data sets for the prediction of the performance metric, peak cooling load. Peak cooling load is a performance metric required for the robustness assessment of IBS's for which no explicit reference data set is available. As robustness is a problem that addresses the future performance of IBS's, both of the reference data sets, the original and projected, were tested.



**Figure 4.6 Peak cooling load; from 20 historic weather data sets - distribution indicated by mean, median, 5th and 95th percentiles; and from 4 artificial reference weather data.**



**Figure 4.7 Peak cooling load; from 20 projected weather data sets (KNMI W+ scenario) - distribution indicated by mean, median, 5th and 95th percentiles; and from 4 projected artificial reference weather data.**

See Appendix E – Climate data applicability for details about the office room used for the case study. The study was conducted for annual and peak cooling demand. The results for the annual cooling demand can also be found in the named Appendix.

The results for the peak cooling load indicate that the artificial reference data sets are not representative for the data sets of the measured historic weather data. The results from the artificial reference data sets are clustered in no logical order around the upper end of the predicted peak cooling loads.

However, the missing logic in the order of the data points indicates that the dry bulb temperature, as selection criteria for the compilation of the artificial reference files, does not dominate the peak cooling load. The most extreme data set, Comf 1%, shows the lowest peak cooling load.

It is confirmed that neither the original nor the artificial reference data can be used to predict uncertainty ranges for the peak cooling load, a performance metric alien to the statistical selection procedure. The selection procedure targets particular climate parameters and building types by using selection criteria specific to a certain building type for example, the building time constant. The different ranking of the artificial reference data sets nicely indicates the different sensitivity of the performance metrics annual cooling demand and peak cooling load for the specific case at hand.

#### *Influence of building characteristics*

Little is known about the severity of the response of specific performance metrics to the climate data used. Clarke (2001) characterized residential buildings using the parameters: capacity, capacity location, window size, infiltration rate and insulation level to categorize typical constructions. Still, the work excludes HVAC system parameters that define the response of integrated building systems to climate variations. Hensen (1999) highlighted problems associated with artificial reference data sets. He states that weather parameters, such as temperature, solar radiation and wind, are not necessarily correlated. When selecting days or months to compile an artificial reference data set, the specific applied parameter weights might not correspond to the sensitivities of the building under study. Hensen refers to different building types to illustrate the problem. A building with a high window to wall ratio – type: solar collector - might react most sensitively to variations in solar radiation, whilst a building with no windows - type: repository - is expected to be most sensitive to changes in temperature. As artificial reference data sets are typically purpose bound, e.g. annual energy demand and overheating risk assessment, they need to be carefully chosen for the specific type of performance study and “ideally” also for the type of building at hand.

#### **Robustness assessment of HVAC systems**

Whereas the previous case study targeted the system parameter peak cooling load as performance metric, here the annual cooling demand and the number of hours above the adaptive temperature limit of 80% are applied.

The case study considers one intermediate floor based on the layout of the office tower ‘La tour’ in Apeldoorn, The Netherlands. For the robustness assessment the performance of three conditioning concepts are investigated; top-cooling, floor cooling and the application of 4-pipe fan coil units. As climate change leads in the Netherlands to warmer and dryer summers, the investigation is limited to the period of April to September. (The reader is referred to the paragraphs “Case description” and “HVAC-concept alternatives” in Appendix F.)

The three concepts are sized to maintain an equal thermal comfort quality. The criterion used is zero hours above the ATL of 80% for the reference year De Bilt 64/65. The cooling capacity is limited to maintain the target criteria. The concepts are then exposed to reference data sets derived from projected climate data.

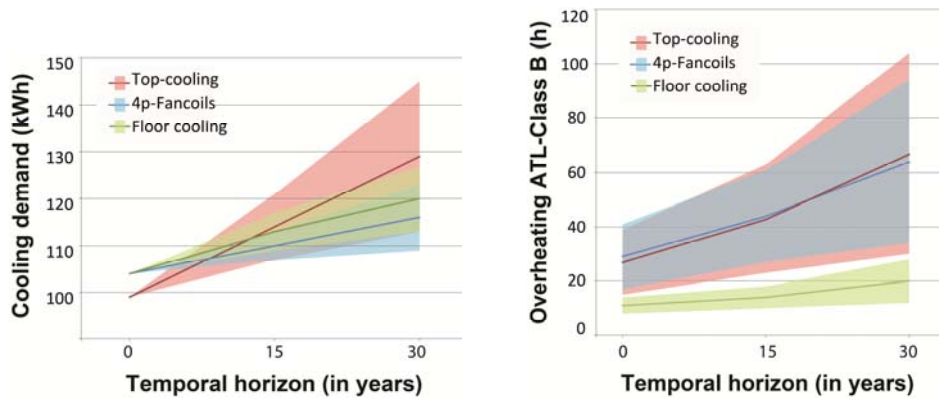
For the estimation of the uncertainty of the annual cooling, four data sets were used, representing the four change scenarios for the Netherlands W, W+, G and G+. For calculating the uncertainty in the number of hours above the ATL of 80%, 12 data sets were used; the three files 1%, 2% and 5% for each of the four change scenarios.

*Cooling demand*

The results in Figure 4.8 indicate that for top-cooling an uncertainty band exists which is twice as wide as that for the 4p-fancoil and floor-cooling concepts for the 30 years projection. Whilst it gives the smallest energy demand for the three concepts at 0 years, its mean gives the highest demand over 30 years with an increase of the factor 1.3.

The floor cooling and 4p-fancoil concepts initially show a higher cooling demand than the top-cooling concept. However, for the 15 years of projected data the mean for top cooling shows the highest cooling energy demand of the three.

The 30 year projections indicate the lowest energy demand for the 4p-fancoil units, followed by the floor cooling concept. Top-cooling gives the highest demand.



**Figure 4.8** Uncertainty band ( $\mu \pm 1\sigma$ ) of annual cooling demand for two temporal horizons, 15 and 30 years.

**Figure 4.9** Uncertainty band ( $\mu \pm 1\sigma$ ) of number of hours above ATL80% for two temporal horizons, 15 and 30 years.

*Adaptive temperature limit 80%*

The number of hours above the adaptive temperature limit of 80% shows a different ranking. The least number of hours are indicated by the floor cooling concept with a moderate maximal  $\sigma$  of 8h over 30 years. The uncertainty for the 4p-fancoils and top cooling are 4 and 4.5 times higher, respectively. The uncertainty band for floor cooling does not overlap with the bands for top-cooling and 4p-fancoils.

## **4.2 Concluding remarks**

Fragmented studies report parametric input for characterizing building specification uncertainties. To the author's best knowledge, no efforts are reported which validate the data with respect to their local representativeness, actuality and applicability. One feasible approach is the measurement and surveying of data sources to test the validity of data. In section 4.2.2 Occupancy pattern, an effort is reported to test the local representativeness and applicability of occupancy design data against results from a building survey.

However, the generalization of derived models is rarely possible due to the used of the raw data. The raw data is typically obtained from controlled environments for a specific purpose.

Scenarios are commonly used in buildings design. It is common practice to use "normative" scenarios to prove compliance with design standards. The use of "exploratory" scenarios is less common. However, exploratory scenarios are required as input to assess the potential future performance of design alternatives.

Scenario based load profiles have to be locally representative, up-to date and they need to match workplace culture as well as building type. To investigate the compliance of design data with the criteria, an office building was surveyed.

The survey results suggest that the consulted design guides still provide feasible data. However, it has to be acknowledged that the design should be based on the lower end of the provided scale. The cooling demand for the office would be overestimated using medium high internal design data for Dutch office buildings for the period considered.

The empirical data confirms the trend towards decreasing equipment gains and proportionally increasing gains by lighting. The observed occupancy profiles do not show significant deviation among them. However, they deviate from the standard profiles, indicating the influence of the workplace culture. The occupancy profiles for the office spaces show similar trends to published data but indicate a higher people presence in the afternoon and on average of two extra working hours.

The urban heat island effect and climate change require the assessment of the building performance under possible future conditions. For this purpose data sets are required which represent the change and variability of the weather variables. In cooperation with VABI BV future climate data sets were generated using the imposed offset method. The data sets were developed for different temporal horizons. From the projected data reference data sets were derived and used with simulation studies. For the first time exploratory scenarios have been made available for the Netherlands to facilitate the assessment of the future performance robustness of design alternatives.

Reference years are typically generated for a specific purpose, such as overheating risk assessment or energy predictions.

That is why prior to assessing the robustness of three HVAC design concepts, the reference data sets were tested on their feasibility to predict the peak cooling load. It was confirmed that neither the original nor the artificial reference data can be used to predict uncertainty ranges for the peak cooling load, a performance metric alien to the statistical selection procedure. The selection procedure targets particular climate parameters and building types by using selection criteria specific to a certain building type as for example the buildings time constant. The different ranking of the artificial reference data sets nicely indicates the different sensitivity of the performance metrics annual cooling demand and peak cooling load for the specific case at hand.

In a subsequent step the robustness of three HVAC concepts was investigated. The concepts considered were floor cooling, top-cooling and 4p-fancoils. It was found that the reference data sets from the projected 15 and 30 years provide a good basis for a relative robustness assessment. From the concept comparison it can be concluded that the floor cooling concept provides the most stable and favorable condition with the least uncertainty within the office space during the considered summer period.

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# 5

## Conceptual design support

Chapter 5 outlines the challenges of using BPS-tools for early design support. It is concerned with determining what system elements designers select to compile design alternatives. This determination allows requirements for the use of BPS-tools during the early design stages to be derived. The derived requirements allow the BPS tool to be extended with the capability to conduct uncertainty propagation and sensitivity analysis. This extended capability is demonstrated on a fictional case study. Chapter 5 addresses three research questions:

1. What are the challenges in conceptual building design related to the use of BPS?
2. What is the extent and content of the option space used by climate engineers and architects to generate integrated design concepts?
3. What are the practical benefits of using BPS-tools extended with the capability to perform uncertainty and sensitivity analysis for conceptual building design?

Question one is addressed by introducing the reader to the character of design problems in building design, and from there challenges for the designer are derived. As the chosen design process model needs to fit the character of the problem, three perspectives on the design process are identified. The value perspective is elaborated on in more detail because the success of a development depends on how good its final performance meets the stakeholder values. In addition, the potential of using engineering analysis tools related to the tasks during the conceptual design stage is considered.

Question two is concerned with the extent of the option space and is addressed by conducting empirical research exploiting three data sources; observation of artificial design projects, review of real design projects and interviews with experts practitioners. The findings are then related to the capabilities of state of the art tools and then requirements are derived for the extended BPS-tool with the capability to conduct uncertainty and sensitivity analysis.

Question three is related to testing the feasibility of using the extended BPS-tool in design practice. This feasibility test is carried out on a case study. For a representative architectural layout, two design alternatives are defined. The design alternatives are evaluated and compared based on the output range of two performance metrics; number of hours above the adaptive temperature limit of 80%, and final energy use for heating and cooling.

Furthermore, sensitivity analysis is conducted to identify the input parameters that have the maximum impact on the output range of the critical performance metric for the favored design alternative. The goal here is to minimize the uncertainty of the simulation output. Conclusions are drawn with regards to the feasibility of the implemented methodology and the expected benefits for design practice.

### **5.1 Design problem, process & tool support**

When aiming at supporting the early stage in building design with BPS-tools one must acknowledge the characteristics and needs of that stage as part of the overall process. The design process can be considered as a vehicle to move from a design problem to a design solution that meets the needs of the stakeholders. The ability of the design solution to fulfill the stakeholders' needs defines the value of the design to the stakeholders. Stakeholder needs require a specific functionality of the integrated building concept. However, design problem characteristics require a number of design solutions to be synthesized and evaluated. To be able to successfully use a BPS-tool to evaluate design alternatives, it needs to be able to represent the elements used to synthesize design alternatives in design practice. Sections 5.1 and 5.2 present re-workings of key sections of earlier published work; see Struck et al. (2009a).

#### **5.1.1 The character of design problem & process**

The description of the process depends on the nature of the problem to be solved. In building design, design problems are referred to as "ill-defined" or "wicked" (Rooijackers and Robinson, 2002) (Papamichael and Protzen, 1993). Rittel and Weber (1973) characterize wicked problems as follows:

1. There is no definite formulation of a wicked problem.
2. Wicked problems have no stopping rule.
3. Solutions to wicked problems are not true-or-false, but good-or-bad.
4. There is no immediate and no ultimate test of a solution to a wicked problem.
5. Every solution to a wicked problem is a "one-shot operation"; because there is no opportunity to learn by trial and error, every attempt counts significantly.
6. Wicked problems do not have an enumerable set of potential solutions, nor is there a well-described set of permissible operations that may be incorporated into the plan.
7. Every wicked problem is essentially unique.
8. Every wicked problem can be considered to be a symptom of another problem.

The problem is, following Rittel and Weber, by character a social challenge due to the large number of interacting stakeholders involved.



Thereby, the design develops iteratively, whereby the design is partly or fully revised to accommodate changes. In the context of climate change, Auld et al. (2007) define "super-wicked problems". However, super wicked problems are not elaborated on further as their extra-characteristic's "Time is running out", "No central authority", "Those seeking to end the problem are also causing it" do not apply.

### ***Design process perspectives***

There are a great number of publications that deal with the design process in construction and engineering disciplines. Important texts have been written by Simon (1969), Lawson (1980), Cross (1994), and Roozenburg and Eekels (1995). Different models have been developed describing the design process in general; an overview of the classic theoretical models by Hall, Darke, Lawson, March, Pahl and Beitz, Pugh and Cross is provided in Birmingham *et al* (1997). More recent contributions continue to expand the field knowledge by targeting, e.g., human factors, participatory-, user-centered- and human centered design (Keinonen, 2009) or the development of information systems that support project design (Hartmann et al., 2009, Moum et al., 2009).

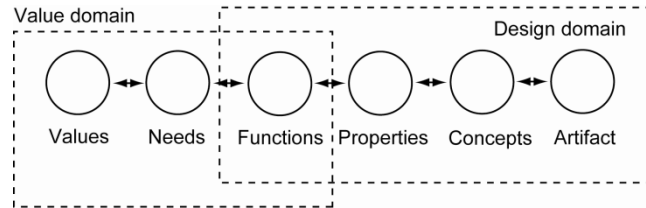
Koskela et al. (2002) discern three perspectives to view design: transformation; flow and value generation; abbreviated TFV-conceptualization of design. The TFV conceptualization is particularly interesting as it enables a categorization and comparison of different process models.

1. The transformation conceptualization is based on the transformation of design requirements to a design specification. The conceptualization excludes the consideration of time and customers and is representative of the conventional phased approaches as in for instance the well-known RIBA design stages (RIBA, 2007).
2. The flow perspective relates to viewing the process as a flow of information as is applied in concurrent engineering methods, e.g. set based design. Efforts are reported by Parrish et al. (2007, 2008) applying set based design to the construction industry. Pektas et al. (2006) use the information flow perspective in design to manage iterative information cycles for process management.
3. The value generation perspective is concerned with generating value to fulfill the customer's requirements. The main principles applicable are the elimination of value loss during the process relative to the maximum value that can be achieved (Koskela et al., 2002).

Here the author makes use of the locally accepted phasing, which distinguishes between five phases, based on recognizable end-products. Those phases are feasibility study, conceptual design, preliminary design, final design and preparation of building specification and construction drawings.

**Connecting the value domain with the design domain**

Work which relates to value generation and provision in construction is published by Rutten et al. (1998). Rutten connects the value domain via functions to the design domain, see Figure 5.1.



**Figure 5.1 The generic design structure: value domain and design domain (Rutten and Trum, 2001)**

Rutten points out that by character the artifacts values are stakeholders specific. The values are converted into needs. From the needs, functions can be formulated to meet those needs. Rutten identifies the six values: well-being, functional value, local value, ecological value, strategic value, economic value.<sup>1</sup>

In one example of a stakeholder, say an office building occupant, a pleasant indoor environment is considered particularly valuable. Rutten defines a need as the underlying requirement to fulfill the value. Examples of needs might be thermal comfort, day lighting or good air quality. The function of an artifact is to provide thermal comfort, by, for example, being able to heat and cool the space, see Table 5.1.

Properties can be understood to describe the expected behavior of an artifact under certain conditions. Rutten follows the argumentation of Roozenburg and Eekels (1995) and differentiates between intensive and extensive properties. Intensive properties relate to the physical and chemical properties of the artifact. Extensive properties are arrived at by the application of causal models on the artifact.

Referring back to the example, corresponding properties are e.g., the mass flow, specific heat capacity and temperature change of the energy transport medium. From this information, one can derive the extensive properties such as cooling capacity or heating capacity.

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<sup>1</sup> The value specific key stakeholders are respectively, the individual, the organization, the local community, the global community, the potential user and the owner.

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In this thesis the author adopts the definition of design concepts by Bax and Trum (1993) who define concepts as:

*“...notional and imaginary representations of artifacts, abstractions of a desired reality that depict or describe the essence of what is needed for the artifact - or process - to fulfill the relevant functions in order to meet the objectives. A concept mediates between a notion, which is an abstract idea with a general nature, and an image, which has a concrete form with a specific nature.”*

It may help to consider an example of a potential cooling concept, such as displacement cooling. Displacement cooling is a concept where air is introduced to a space at 2-5K below room air temperature, providing buoyancy driven cooling around present heat sources. The concepts are further detailed and integrated to develop the artifact; an integrated building system.

**Table 5.1 Exemplified generic design structure for two needs derived from basic value for building occupants – well being**

Value	Need	Function	Property	Concept	Artifact
Well being	Thermal comfort	Provide comfort cooling	Cooling capacities	Displacement cooling	Integrated building system
Well being	Day lighting	Allow the building envelope to admit daylight	Glass to wall ratio of external wall	Fully glazed facade	Integrated building system

**Design iterations**

A starting point of the current research is that independent of which perspective the process is viewed, a common challenge is dealing with design iterations that form a natural part of the underlying cyclic ‘synthesis–analysis–evaluation’ design principle. Pektas et al. (2006), based on Eppinger’s work (1994), differentiate between:

1. expected design iterations, and
2. unexpected design iterations.

As an example, an unexpected iteration may result from a failure of the design proposal to meet the posed required performance.

An expected iteration may result from the need to revisit design decisions that were based on assumptions or incomplete data sets. Pektas, following the suggestion from Browning (1998), proposes two options to manage expected iterations; reducing their numbers and reducing the time needed to complete them. The first option is only possible to achieve by restructuring the design process, which is the aim of concurrent design approaches (Hopfe et al., 2006b).

The second option, increasing the speed, can be facilitated by different measures, e.g.:

- improving coordination,
- limiting extraneous activities, and
- using engineering analysis tools.

### **5.1.2 Evaluation of building design concepts**

The focus during conceptual design is on the synthesis of integrated design alternatives. The early design stages are characterized by the need to evaluate a large number of design representations of different abstraction levels with insufficient knowledge about the interaction of design variables and sub-systems (Matthews, 2008). The ill structured character of design problems hinders the clear definition of the option space (Stouffs, 2008). As a consequence, not one but a number of design representations, also called concepts, are required to outline the option space.

In design practice this problem is approached with case based reasoning (Mora et al., 2008). Designers re-use their experience collected in earlier design projects. The quality of the resulting design solution is thereby directly influenced by the extent of professional experience. Stouffs (2008) states that the developed design representations are both means and products. They are means because the design problem shifts and evolves during the definition process, and products because they represent solutions to the earlier stated design problems.

#### ***Steps in conceptual design***

Arafat (1991), based on work of Arciszewski, defines characteristic steps for the conceptual design stage, taking into account the “wicked” nature of design problems.

1. Identification of existing or expected needs;
2. Design problem formulation;
3. Design problem analysis;
4. Determination of solution space;
5. Generation of concepts;
6. Feasibility analysis of concepts;
7. Evaluation of feasible concepts;
8. Comparison of the most promising concepts;
9. Presentation of the most promising concepts.

Arafat accounts for the nature of design problems by considering a space of potential solutions from which a number of concepts to compile integrated design alternatives are selected for evaluation.

The space of solutions is from here on referred to as “option space”. Since the design problem evolves with the definition of a potential solution, the process can be characterized as a stochastic process

Here the author of this thesis concentrates on the evaluation and comparison of feasible and the most promising concepts, respectively. Building performance simulation tools are the tools of choice.

### ***The option space***

The option space is the pool of alternative components and subsystems that serve as input to compile design alternatives for integrated building systems. There are a number of explicit constraints that limit the option space from the beginning of the building design process. First of all, there are the building regulations that prescribe e.g., a minimum thermal performance of the building. Secondly, there is the design brief, which defines the design requirements in a given urban context for a specific development. Another aspect that has the potential to implicitly influence the extent of the option space is the configuration and working conditions of the design team. The above constraints on the option space are not further elaborated on because the focus of the work is on its content rather than its extent.

### ***BPS-tools for the evaluation of design alternatives***

To justify their use, BPS tools have to match the character of the design stage and the needs of the involved engineering disciplines. Clarke (2001) recognized that the tool-box use of design tools needs to evolve in computer supported building design environments. Augenbroe (1992) associated two general approaches to the development of analysis tools; the technology-push and the technology-pull approaches. The technology pull approach is characterized as being driven by demand in the form of design questions, e.g. introducing simplified tools to design practice responding to the need of design practice for simplified tools. The push approach embraces design oriented improvements of sophisticated tools. What current tool development lacks is the focus on multi-disciplinary design teams. Mora (2008) gives a good overview of requirements to support conceptual structural design. His requirements also apply here. The most important development requirements relating to the conceptual design stages are:

- Assisting rather than automating design,
- Facilitating the quick generation of integrated design alternatives,
- Shortening synthesis-analysis-evaluation cycles,
- Supporting the exploration of the option space for the selection of the most suitable design alternatives.

The requirements relate to a number of characteristic steps in conceptual design, such as the determination of the option space as well as generation and evaluation of concepts.

### **5.2 Use and content of the option space**

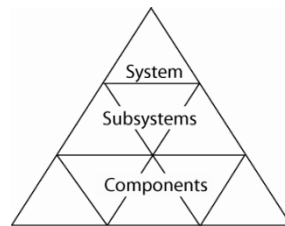
To support the exploration of the option space and facilitate the shortening of the synthesis-analysis-evaluation cycles, BPS-tools need to be able to represent what practitioners use to compile design alternatives. This section is dedicated to the content of the option space and its use. Different user groups are considered, such as expert practitioners and building construction students. Empirical data from three sources is categorized and analyzed. The data originates from student design projects, a review of realized building design projects, and interviews with practitioners. For the categorization and subsequent analysis, system elements are introduced.

This three-pronged approach allows findings to be inter-related, and thereby overcomes some of the problems inherent in following one line of research only. The findings are related to the capabilities of state of the art tools and requirements derived for future generation BPS-tool extended with techniques for uncertainty and sensitivity analysis.

#### **5.2.1 Systems theory**

Systems theory presents a formal framework for the description of processes and the hierarchy of components. It was derived from processes found in nature, design and engineering. Studies have been reported which relate building design to systems engineering (Djunaedy et al., 2006, Kanagaraj and Mahalingam, 2011, Yahiaoui et al., 2006).

By applying systems theory, an integrated building system can be decomposed - using a top down approach - into elements in the form of components, attributes and relationships. The components represent the operating parts of the system and are characterized by attributes and relationships (Blanchard and Fabrycky, 2006). Blanchard et al. define the purpose of the conceptual design stage as being to predetermine the function, form, cost, and development schedule of the desired system.



**Figure 5.2 System decomposition**

### ***Integrated building system view***

The integrated building system view considers the building performance holistically as a result of the relationship between all its component attributes. It is therefore required to introduce definitions of the system elements.

An example identifying individual system elements in the context of an integrated building system is provided below. A system can be decomposed into subsystems applying different perspectives. Mallory Hill (2004) identified three different perspectives to decompose an integrated building system, which are related to building, architecture and human. For example, when choosing the “building perspective” a system can be decomposed into its subsystems: structure, skin, services, fit-out and communications. Zooming in on services allows the system “energy services” to be decomposed into subsystems for conversion (chemical to thermal), distribution (air or water based) and the exchange terminals at room level. Components are system elements that define a subsystem.

### ***System and subsystems***

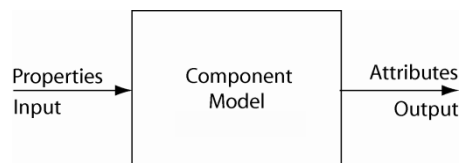
If one, for example, considers the supply side of a mechanical ventilation system, a subsystem of an integrated building system, it can be decomposed into components such as the following; air handling unit, ductwork and supply air grille.

Depending on the purpose of the system description and required level of detail one can consider the air handling unit for example a subsystem of the mechanical ventilation system. The subsystem can further be decomposed into its components inlet grille, silencer, fan, heating coil and cooling coil.

### ***System elements: Components, properties and relationships***

Whilst Rutten (1998) separates extensive and intensive properties, system theory differentiates between properties and attributes. Whereas, Rutten’s intensive properties relate to properties in system theory, his extensive properties relate to attributes.

Component properties are properties which define the component’s dimensions and materials. In the context of a component model, the physical properties define the model input (see Figure 5.3).



***Figure 5.3 Concept of a component model***

Component attributes are characteristics or qualities of the component related to the subsystem. In the context of a component model, attributes define the output.

Component relationships are the links between components and attributes to serve a purpose by providing a specific function.

***Example of a component model***

An example is used to clarify the model description. Consider a single layered wall separating the internal environment from the outside.

The heat transfer through the wall is represented using the design thermal u-value as a descriptive model.

The component properties of the wall representing the model input are: thermal conductivity, layer thickness and convective heat transfer coefficients on both faces. The model provides the component attribute, design thermal u-value, which characterizes the wall's heat transfer under design conditions. The model output serves as characteristic input for other component models such as to determine the heat loss of the office space.

**5.2.2 Empirical research**

There are a great number of approaches to conduct empirical research in design practice. The focus of an approach can either be on a real design process or on artificial experiments. Due to the complexity and time required to complete real-life design processes, it takes a significant effort to gather empirical data (Emmitt, 2001, Pahl et al., 1999). Still, working on real processes does allow the study of the process embedded in the organizational and social frameworks providing its contexts (Pahl et al., 1999). Different to real process, artificial design processes are more focused on one line of research ,e.g. Macmillan (2000) and Austin et al. (2001). The specific focus provides the opportunity to highlight individual aspects of the process and compare the performance of teams working on similar tasks. Still, the context provided by real design processes is missing. Investigating design projects can happen directly or indirectly. A non-participating person records the progressing design during direct observations. In direct observations the design team documents the process progress themselves using interviews, diary sheets or questionnaires

***Artificial (student) design project observations***

During the winter semester of 2007 students at the University of Plymouth (School of Architecture, Design and Environment) were asked to develop a design based on a predefined design brief in multi-disciplinary teams. The participating students are studying towards degrees in architectural technology, construction management, building and environmental construction surveying.

The design brief required the students to design a large, multi-functional facility for the Faculty of Technology at the University of Plymouth, on a constrained location which borders different buildings in every direction. The design needs to provide laboratory space plus new teaching, research and administration spaces.



It is to be a landmark building in terms of architecture, fitting in with the high-tech image of the surrounding Roland Levinsky, Portland Square and Rolle Buildings. Furthermore, the building is expected to be a state-of-the-art facility, with high sustainability, flexibility and wellbeing credentials, so that it takes on the role of the flagship building of the University.

The student design projects allow the study of different teams working with the same brief, who are developing their projects for the same building site and within the same constraints. As this is only a twelve week project, the design time is limited, allowing the study to be reasonably compact. The observation is carried out by direct observation of the lecturer, who also undertakes the studio teaching, from the very first moment (student briefing) to the end of the project (student presentations). This organization allows for full access to intermediate design products. The study of student design projects, however, has the drawback that students are not fully trained and experienced design professionals. Furthermore, there is no tangible product (building) that represents the end stage that could be used to measure a point in time where uncertainties related to design attributes have been reduced to zero.

The work was conducted in close collaboration between the University of Plymouth and the TU/e. While the student observations were conducted in Plymouth, the data analysis and interrelation with the remaining two data sources was conducted in Eindhoven. The observation was partly pre-structured and partly open. A checklist of relevant system elements was used, see Table G.7.8 (Appendix). The checklist was augmented with the notion of “non-predefined points”, to be noted during the surgeries and added as per occurrence.

#### ***Real-life design project review***

The material of three previously reported case studies is revisited and data is extracted that contributes to the work on the option space (Wilde, 2004). The case studies focus on real-life projects from actual design practice that have been constructed in the Netherlands. In this condition, actors are professionals and are working in their normal context and within real constraints. Originally, the data was collected by indirect observations, through interviews, and through the review of design documentation such as reports and drawings and architectural models. The three case studies are the Rijnland Office in the city of Leiden, ECN Building 42 in Petten, and the Dynamic office Kennemerplein in Haarlem.

#### ***Interviews with expert practitioners***

In 2005, 12 unstructured interviews with international building expert practitioners were conducted and analyzed. The results were published in Hopfe et al. (2006d). The aim was to gain insight into their experience and knowledge concerning the design process and the use of computational tools for design guidance.

Four important aspects were addressed: practitioner’s appreciation of the different design process stages; their role in each phase; which computational support is being used and how; and the identification of shortcomings of current computational support. The interviewees are active in different engineering disciplines, including climate and civil engineering, building physics, and architecture, see Hopfe et al. (2005).

**Table 5.2 Overview of data characteristics**

	Artificial design projects	Real-life design Projects	Expert practitioners view
Aim	Training integrated design in an education environment	Obtaining insight into evaluation and selection process for energy saving components in design practice and use of computational tools for support.	Understanding where practitioners use BPS; Identification of benefits and drawbacks.
Method	Observation of student projects.	Interviews with practitioners & Review of project design documentation	Interviews with practitioners
Character	<b>Transient</b> process – Project specific; Integrated design; Educational environment	<b>Real</b> early design setting Project specific; Review across multiple disciplines (architects, HVAC consultant, simulation specialist).	Review of <b>ideal</b> early design expectation and experience; Non-project specific; Discipline specific.

Table 5.2 indicates the characteristics of the collected data. All three research activities have in common that they target integrated building alternatives during the early design stages. The number of design disciplines participating was the largest for the student projects and the smallest for the real-life case studies. One important difference between the data collections is the time at which the data was collected. Whilst the student projects were observed in real time, the real-life design projects were reviewed after the completion of the design. In contrast to the student design projects, the interviews with practitioners do not relate to one design project, but to the practitioners’ discipline specific design experience. During these interviews many design projects were named and discussed to illustrate particular problems and approaches to solutions.

### **5.2.3 Data analysis**

A comparative data analysis using counts was conducted based on formatted and categorized data. The data was analyzed to establish the extent to which students use different system elements for building design. Another point of interest was whether system elements could be identified to appear repetitively. The number of occurrences could then be used as measure for importance. This would allow a comparison with results from the other two research initiatives. In addition, the number of system elements considered during the progressing design was mapped across the groups.

#### ***Data formatting and categorization***

The data collected from different people and by different research initiatives naturally comes in non-uniform formats. To allow for a thorough analysis of the data, first it had to be formatted. After formatting it was categorized as elements of a system. Component attributes and properties were grouped into one category called attribute. The final categories used are component, attribute and relationship.

The process of formatting and categorization poses a source of errors if the context in which the data was presented cannot be captured. An example of data formatting is given for the attribute 'functional zoning'. Bearing in mind the original context - separation of volumes for specific use - the extracted raw data points with the same meaning as 'arrangements of space and function' and 'topology' were grouped and described as data points relating to 'functional zoning' to establish counts.

As an example of categorizing data, consider the observed data point 'steel frame for main structure', recorded for group 03 during the design studio in the second week of the project. The data point could either be categorized as an attribute, emphasizing 'steel', or as component, emphasizing 'main structure'. As the data points available indicated that the design team considered different materials for different building sections, it was categorized as an attribute. The comparative data analysis using counts is based on formatted and categorized data. Extracts of the collected data from the three data sources, formatted and categorized, are presented in Table G.7.9, Table G.7.10 and Table G.7.11.

#### ***Discussion***

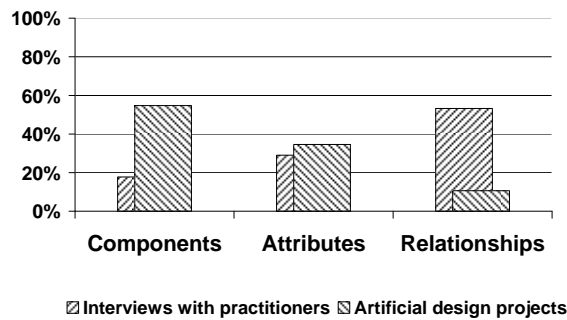
The extent of the option space can be estimated by making use of the identified elements. From the data obtained a number of characteristics and categories could be derived (see table Table 5.3).

**Table 5.3 Identified attribute characteristics, component categories, relationships and associated values.**

Pos.	Property and Attribute characteristics	Subsystem categories	Relationships	Values associated to relationships
1	Discrete (e.g., location)	Architecture (e.g., Functional zones)	Building – Owner	Economic value (e.g., Running costs)
2	Continuous (e.g., Solar gains)	Building services (e.g., Cooling system)	Building - Environment	Ecological value (e.g., Energy use)
3		Structure (e.g., Steel frame)	Building - Occupants	Basic value (e.g., Comfort)
4		Façade (e.g., Climate facade)	Building - Time	Strategic value (e.g., Flexibility)

Two characteristics are feasible for the representation of attributes, discrete and continuous. The components could be categorized into four subsystems: architecture, building services, structure, and façade. Further, four types of relationships were identified; which correspond to values such as well-being, economic- , functional- , and ecological value. Literature on the subject (Brand, 1995, Rutten et al., 1998) suggests that there are more categories characterizing the option space in building design when diverting the attention from the collected data and targeted engineering domains. Brand (1995), for instance, identifies other component categories, separated by so-called “shearing layers”, such as space plan, and interior. “Shearing layers” contain building components with different life expectancies.

The extent of the option space depends on a number of variables such as design context, participating engineering disciplines and design requirements. The results indicate that students predominantly use components for concept design whilst expert practitioners make extensive use of relationships. In fact, the least considered element by the students is relationships, while the least considered element by expert practitioners is components. The weights of three elements from real-life projects follow the trend noticed in the student design projects, although they show slightly smaller numbers for all three elements (see Figure 5.4).



**Figure 5.4 Comparison of attributes, components and relationships from interviews and student projects**

It was expected that the data from real-life projects would follow the trend derived from interviews with expert practitioners. This expectation was not confirmed. Therefore, the data has been excluded from Figure 5.4.

There are a number of factors that may contribute to explaining the observation:

1. *Time of project review.* The real-life projects were reviewed rather than observed. The review took place after completion of the design, thereby naturally limiting the perspective to identified solutions for a well-defined design problem. This is different to the characteristics of the early design stages, where the design problem is not yet defined and the number of possible design solutions is significant.
2. *Size of the sample set.* Three real-life projects were observed, which might be too small a sample from which to derive representative conclusions.
3. *Review perspective.* The perspective of the review was limited to energy saving building components, which limits the considered relationships to building– environment, indicated by energy demand.

Due to the identified limits, the data does not give a complete overview of the attributes, components and relationships considered during design development. However, the data is sufficient for considering the extent of the option space. The preliminary option space derived from real-life design projects, student design projects and interviews with expert practitioners consists of a large number of attributes, four component categories and a large number of indicators for four different types of relationships.

The observed difference in how expert practitioners and students or, put differently, novice designers, approach design corresponds to findings published by Ball (2004). Ball argues that expert designers work in a scheme or relationship driven manner, whilst novice designers work in a solution or case-driven manner.

However, experts do not exclusively work with relationships but also make use of case based reasoning where design problems are unfamiliar or resistant to relationship driven design approaches.

### **Conclusions**

This reported study explores the design option space from three different research activities; student design projects, real-life building projects and interviews with expert practitioners. The question of interest here was: “What is the extent and content of the option space used by climate engineers and architects to generate integrated design alternatives”.

It was found that the option space uncovered from the three research initiatives contains items that could be categorized as system elements, such as attributes, components and relationships. The data shows that expert practitioners and students (novice designers) make use of all three elements but to a different extent.

Corresponding with work of others, it was found that students tend to work with components, whilst practitioners tend to work with relationships.

### **5.3 Application of uncertainty propagation and sensitivity analysis**

The previous section investigated the handling of the option space by students and expert practitioners during early stages in the design process. This section is concerned with applying uncertainty propagation and sensitivity analysis with one building simulation tool, VA114, to address a realistic design problem. The aim is to test the feasibility of using the methodology to address realistic design problems and to formulate expected benefits of using the implemented methodology in design practice.

VA114, a detailed design analysis tool for the early design stages, was chosen due to the observed differences in predicted uncertainties and sensitivities between a detailed and simplified tool, see section 3.5.1 Tool selection.

It was concluded that it cannot be stated with confidence that the design decision taken based on results from the simplified tool would be the same as a decision taken based on results from the detailed design tool.

With the knowledge obtained from the previous section one can draw conclusions regarding the content of the option space and regarding students’ and expert practitioners’ preferences as how to compile design alternatives. As the aim is to support design practice, the main focus of the current research is on the requirements of expert practitioners.

#### **5.3.1 Definition of the design problem**

It is assumed that a fictional organization requires a new office building. Of particular value to the stakeholder “organization” is the realization of a pleasant indoor environment and low environmental impact.

A realistic design problem was considered. A realistic design problem is here defined as a common problem to which practitioners can relate.

The problem was formulated as: "To identify an integrated building system which satisfactorily integrates two potentially conflicting aspects, to achieve a pleasant indoor environment and a low environmental impact.

The two aspects relate to the basic value of well-being and to ecological value<sup>1</sup>. From the identified values, needs are derived which - when fulfilled by specific functions - indicate a satisfactory performance of the system. However, due to the character of the conceptual design stage, the properties of the concepts are uncertain. From here on concepts are referred to as design alternatives.

To achieve a pleasant indoor environment the stakeholder requires *good thermal comfort*, and a reduction in the environmental impact of the building. Ultimately, the stakeholder wishes to *minimize the final energy demand for heating and cooling*. The design problem relates to two architectural system levels. The "office space" in the case of thermal comfort and "the building" in the case of final energy demand. VA114 is used for the performance predictions. The performance metrics of annual final energy demand and adaptive temperature limit of 80% for beta-type buildings are applied.

### **Performance metrics**

*Final energy demand:* The annual final building energy demand for heating and cooling is the energy required to heat and cool the building over one year, taking into account the system's generation and distribution losses.

*Adaptive temperature limits:* The adaptive temperature limits differentiate between alpha and beta building types. The differentiation is based on the degree of influence individuals can practice on their environment.

Three performance bands of different quality and which are not to be exceeded are defined for both building types. The central band, class B, indicates an acceptance of 80% of the building occupants over the user period of the building. The inner band, class A, presents the most stringent requirement and indicates a high quality thermal environment with an acceptance of 90% of the building occupants.

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<sup>1</sup> Recent publications BROUNEN, D. & KOK, N. On the economics of energy labels in the housing market. *Journal of Environmental Economics and Management*, In Press, Corrected Proof, KOK, N. & JENNEN, M. 2011. De Waarde van Energiezuinigheid en Bereikbaarheid: een Analyse van de Nederlandse Kantorenmarkt. Maastricht/ The Netherlands: European Property Research Institute/ Maastricht University, MEIN, E. Mehr-Wert durch Nachhaltige Immobilien? In: BRANDER, M. I., ed. 16. Herbstseminar Wege zum Plusenergiehaus im Rahmen der 9. Schweizer Hausbau+Energie Messe 11 November 2010 Kongresszentrum, BEA Bern Expo, Bern. Focus Events AG, 5-13. indicate a relationship between low environmental impact and economical value.

The outer band, class C, is the most relaxed, only achieving an acceptance of 65% of the occupants. Class C is not to be applied to new buildings. Acceptance can be granted e.g. for historic buildings to limit the technical and financial burden during refurbishments.

The performance bands are defined by the operative temperature and a derivative of the external air temperature, the four-day running mean outdoor temperature (RMOT). The RMOT is calculated from weighted daily means of the current and the three previous days (ISSO, 2004).

### **5.3.2 Feasibility test of the prototype**

To test the approach using BPS-tools extended with uncertainty propagation and sensitivity analysis for design support, a common design problem from the domain of architecture and climate engineering is applied to a representative architectural layout.

Two design alternatives were developed for the architectural layout. The design alternatives were reviewed and commented on by expert practitioners in individual feedback sessions. Detailed information on how the user feedback was obtained can be found in Chapter 6.

Design parameters specific for the design alternatives were identified. Design parameters describe physical and/or functional characteristics of a component model with respect to achieving one or more performance metrics. The design parameters and range were discussed with expert practitioners.

The computational prototype structure, as described in Chapter 3, was used to evaluate the case studies. The prototype was adapted to the needs of each of the formulated design alternatives.

#### ***Analysis process***

The feasibility of the prototype to explore the option space, facilitating rapid generation and evaluation of design alternatives by uncertainty propagation and sensitivity analysis, is tested.

In cooperation with design practitioners two design alternatives were developed for a representative office building. For each design alternative a virtual building and system model was set up in VA114, forming the base-models for the analysis process.

Due to the conceptual differences between the design alternatives the prototype was adapted accordingly. For DA1 12 input files are manipulated and 9 input files for DA2. In Table 5.4 columns 8 and 9 give details about the manipulated parameters.

The analysis process consists of three steps: (1) uncertainty propagation and normality testing, (2) sensitivity analysis and (3) stepwise regression analysis.

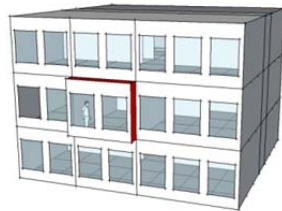


Each of the two prototypes was verified as outlined in 3.4.2 Verification. Further information can be found in 3.3.

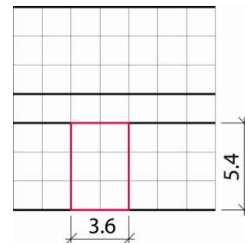
### 5.3.3 Representative architectural layout

To support the feasibility test of the prototype, a three-storey office building is used. It is based on a typical Dutch architectural grid and follows a representative layout and furnishing (ISSO/SBR, 1994). The building is located in De Bilt, The Netherlands. Figure 5.5 shows a three dimensional perspective of the representative architectural layout. The layout is characterized by two office areas facing north and south, respectively, being separated by a central corridor. The floor plan is identical for all three floors.

The south facing zone of the intermediate floor consists of cellular offices. The remaining office space is "open plan". The central cellular office space on the intermediate floor is considered for the assessment of the thermal comfort. The office has one external facade housing the only window. The floor area is  $19.4\text{m}^2$ , defined by an architectural grid of  $3.6\text{m} \times 5.4\text{m}$  (see figure 1). The space is occupied by two people and contains computing equipment and one printer. The office is occupied from 8.00 -18.00.



**Figure 5.5** Fictional architectural layout



**Figure 5.6** Architectural grid of fictional layout

#### **Design alternatives**

Two design alternatives, both integrating architectural and building services components and subsystems, were developed in an iterative process in close cooperation with design practitioners.

The alternatives represent two of a great number of potential subsystem combinations; see 5.2 Use and content of the option space. For the purpose of the subsequent analysis, the chosen design alternatives comply with a number of requirements.

They represent:

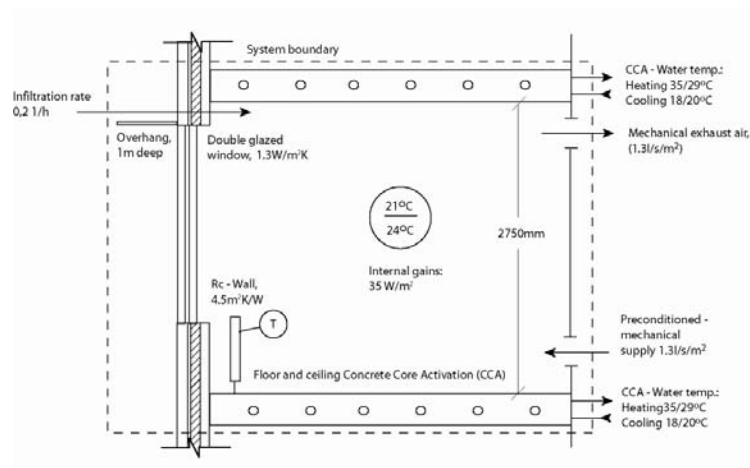
- feasible and realistic design alternatives for the architectural layout;
- non-trivial design alternatives;
- include subsystem and component combination used in design practice;
- conservative and forthcoming design alternatives;
- design alternatives which comply with the current prescriptive and performance based building regulations.

The following passages describe the design alternatives 1 & 2.

*Integrated design alternatives 1 (DA1)*

The focus of DA 1 is on minimizing the final energy demand for heating and cooling by minimizing external gains and heat losses. A 1m deep overhang reduces the solar gains. A good insulated façade plus façade glazing reduces the heat loss to the external ambient. The horizontal room surfaces are activated and exposed to provide base heating and cooling (see Figure 5.7).

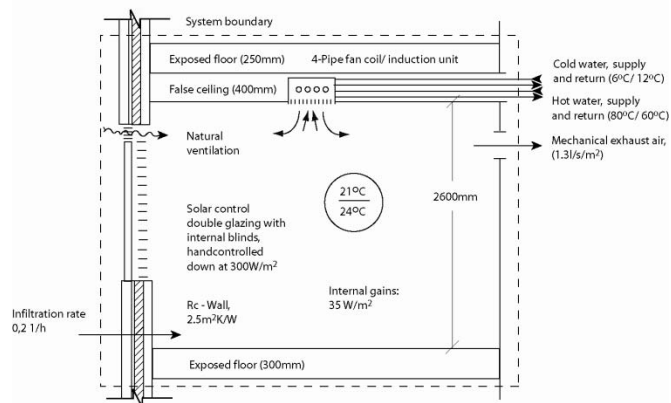
To meet the demand peaks for heating, a radiator is installed. Fresh air is provided at the minimum rate of  $1.3\text{l/s/m}^2$ . The mechanically supplied and extracted air is pre-conditioned.



**Figure 5.7 Design alternative 1—Focus on minimizing the final energy demand**

*Integrated design alternative2 (DA2)*

DA 2 is characterized by the aim to balance the two dominant needs; a thermally comfortable indoor environment and low final energy demand for heating and cooling using conventional “low cost” techniques. The floor is raised. The ceiling is suspended and houses the 4 Pipe fan coil unit. The building makes use of a hybrid ventilation system. The air is supplied naturally and extracted mechanically. The ventilation rate corresponds to the minimum fresh air rate  $1.3\text{l/s/m}^2$ . The space is heated and cooled by the 4 Pipe fan coil unit.



**Figure 5.8 Design alternative 2—Focus on balancing thermal comfort and final energy demand**

**Design parameters and ranges**

For the two design alternatives, parameters and corresponding range(s) were identified for two architectural system levels, office space and building.

The design parameters were associated to the corresponding subsystem categories structure, façade etc. The collected information is presented in Table 5.4. The design parameters and their ranges were reviewed and commented on by expert practitioners in individual feedback sessions.

**Table 5.4 Design parameter and ranges for design alternatives 1 (DA1) & 2(DA2)**

Pos.	System	Architectural subsystem levels	Design parameter	Unit	Min.	Max.	DA1	DA2
1	Building	Building/ Room	Orientation	[deg]	1	360	x	x
2	Façade	Building/ Room	g-value (zta)	[n/a]	0.3	0.7	x	x
3	Façade	Building/ Room	U-value fenestration	[W/m <sup>2</sup> K]	1.1	1.8	x	x
4	Façade	Building/ Room	U-value external wall	[W/m <sup>2</sup> K]	0.2	0.5	x	x
5	Façade	Building/ Room	Internal blinds, control	[W/m <sup>2</sup> ]	250	600	n/a	x
6	Façade	Building/ Room	Infiltration rate	[1/h]	0.15	0.25	x	x
7	Façade	Room	Glass to wall ratio	[n/a]	0.25	0.85	x	x
8	Services/ HVAC	Room	Ratio acoustic to active ceiling	[n/a]	0.15	0.7	x	n/a
9	HVAC	Room	Ventilation rate	[m <sup>3</sup> /h]	91	160	x	x
10	Structure	Room	Thermal active mass	[n/a]	low	high	high	x
11	Interior	Room	Internal gains, equipment + people	[W/m <sup>2</sup> K]	14	50	x	x
12	Services/ Lighting	Building/ Room	Light fittings control	[lux]	400	600	x	x

Probability distributions have to be defined for each model input parameter. A uniform distribution was chosen for the design parameter because it was assumed that the designer working with the design alternatives at this stage of the design has no predetermined preference for the parameters to take one value over another. The uniform parameter distribution assesses the occurrence of all values between the minimum and maximum value as equally likely.

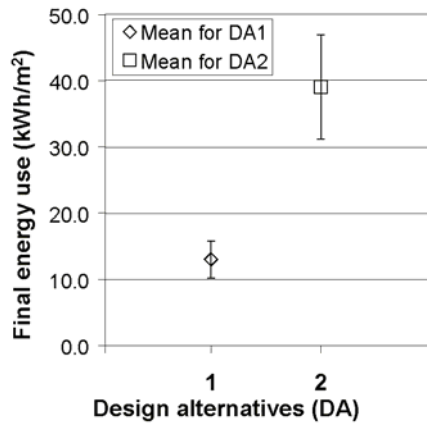
### 5.3.7 Performance evaluation

This section presents the results of the individual analysis steps; (1) uncertainty propagation and normality testing, (2) sensitivity analysis and (3) stepwise regression analysis.

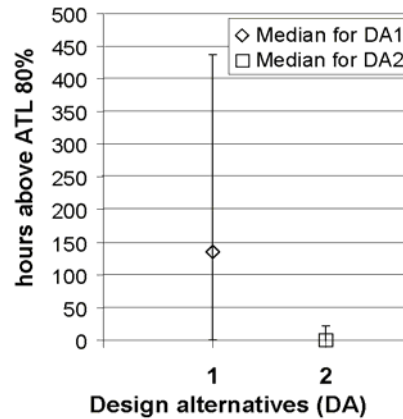
#### **Uncertainty of the performance metrics**

The aim of uncertainty propagation is to quantify the uncertainty in the final energy demand and thermal comfort based on the uncertainty in the design parameters. The process requires: identification of the parameter ranges and their distribution, generation of the sample matrix (n=100), sample propagation, approximation of output distribution and presentation of uncertainties in model output.

Figure 5.9 and Figure 5.10 show the results for the two design alternatives sorted by performance metrics. It should be noted that due to the non-normally distributed data set for the comfort criteria, the median and interquartile range are used to describe the data sets' characteristics. A summary of descriptive statistics for the data sets can be found in Table H.7.14.



**Figure 5.9 Final building energy demand for heating and cooling; Error bars indicate 95% confidence intervals**



**Figure 5.10 Hours above adaptive temperature limit (ATL) 80% for office space, Building type: Beta; Error bars indicate interquartile range.**

The above figures indicate very different performance patterns for the two design alternatives.

DA 1 shows a narrow uncertainty band for final energy use and a wide band for the number of hours above the adaptive temperature limit of 80% (ATL80%). DA 2 shows a high final energy demand with significant uncertainty, but a narrow band near the performance target for the ATL of 80%.

The step towards performing the sensitivity analysis requires making a decision about which of the design alternatives to take forward. It was decided to consider DA1 for a number of reasons:

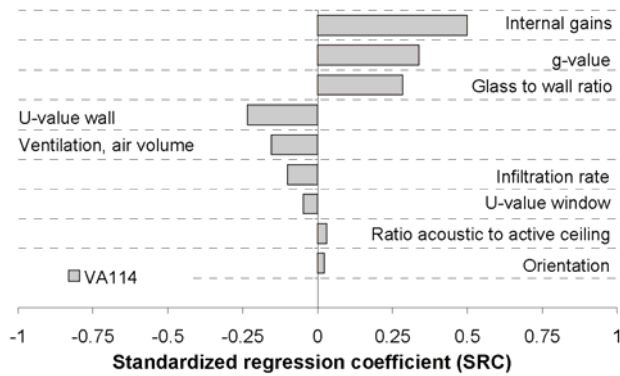
- Design target zero hours above ATL80% for DA2 is realistic to achieve.
- DA 2 uncertainty band for the final energy demand is narrow, indicating a potentially small impact by design parameter uncertainties.
- DA 1 shows a final energy use three-times lower than DA2, with marginal uncertainty.
- The impact of the design parameter uncertainties on the hours above ATG80% for DA 1 is significant – providing a great potential to achieve the design limit of zero hours above ATG80%.

#### **Individual parameter sensitivity**

The aim of the sensitivity analysis is to identify the number of parameters which dominate the width of the ATL of 80% uncertainty band.

In conducting the sensitivity analysis, multiple-regression analysis on Latin hypercube samples is applied. Here, standardized regression coefficients are used since they provide information about the linear effect of the considered parameters.

The bars in Figure 5.11 indicate the sensitivity of the performance metric hours above the ATL of 80% to the nine design parameters. The length of the bars indicates the severity, and the orientation of the bars indicates the direction of impact. It is clear that a severe impact can be related to the parameters internal gains, g-value, glass to wall ratio and U-value wall.



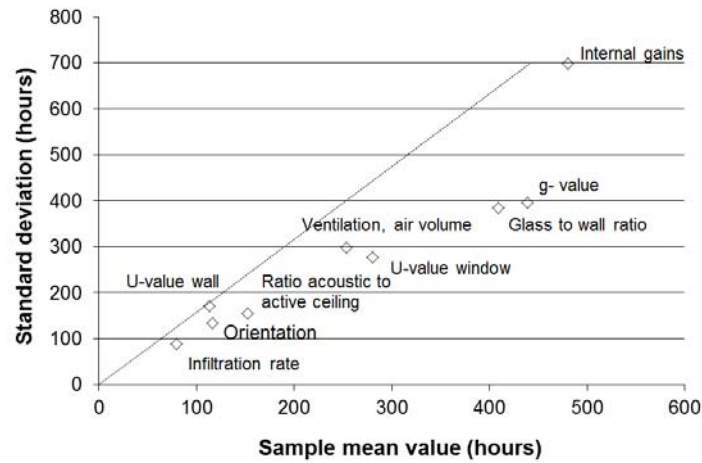
**Figure 5.11 Standardized regression coefficients as sensitivity measure for the performance metric ATL80% for DA1**

However, the use of regression coefficients for sensitivity analysis is conditional on  $R^2$ . If  $R^2$ , the coefficient of determination, is able to explain a large part of the variance of the output, then the regression model is effective and regression coefficients can be used for sensitivity analysis.

In our case  $R^2 = 0.621$ , which translates to 62.1% of the variance in the hours above the ATL of 80%, and can be explained by the range in the input variables. The value is below the suggested minimum threshold of 0.7 (Saltelli et al., 2004). That is why the sensitivities obtained from the regression model are compared to sensitivities obtained from the Morris analysis.

The Morris analysis provides value for interpreting the impact of parameters, the mean value and the standard deviation. The mean value is a measure of the overall parameter impact, and the standard deviation is a measure for parameter interaction and non-linearity.

The results of the Morris analysis confirm the severity of the named parameter's internal gains, g-value and glass to wall ratio in the earlier observed order. However, the U-value wall falls considerably with respect to its overall impact. The Morris analysis places the U-value wall at the second least important parameter.



**Figure 5.12 Mean value & standard deviation of elementary effect as sensitivity measure for the performance metric ATL80% for DA1**

#### **Collective parameter sensitivity**

Morris and multi-regression sensitivity analysis give an indication of the severity of the individual parameter impact. However, what is required to reduce the width of the uncertainty band for the ATG80% is information about the combined severity of the design parameters. This is why step-wise regression is proposed. Table 5.5 shows that the top three parameters are responsible for 85% percent of the variance in the ATL of 80%.

**Table 5.5 Results from stepwise regression analysis on ATL 80% (Beta)**

Step <sup>(a)</sup>	Parameters <sup>(b)</sup>	SRC <sup>(c)</sup>	R <sup>2</sup> <sup>(d)</sup>	R <sup>2</sup> in % <sup>(e)</sup>
1	Internal gains	0.499	0.309	49.7
2	g-value	0.338	0.446	71.7
3	Glass to wall ratio	0.283	0.530	85.3
4	U-value external wall	-0.235	0.584	93.9
5	Ventilation rate	-0.154	0.609	98.0

<sup>(a)</sup> Steps in forward-stepwise regression analysis.

<sup>(b)</sup> Variables listed in the order of selection in regression analysis

<sup>(c)</sup> SRC's for parameters in final regression model.

<sup>(d)</sup> Cumulative R<sup>2</sup> value for each parameter entry to regression model.

<sup>(e)</sup> Cumulative contribution in % for each parameter entry on final R<sup>2</sup>.

The identified parameter set consisting of internal gains, g-value and glass to wall ratio should now be more closely investigated. The set represents those parameters responsible for 85% of the uncertainty in the model output. In a realistic design setting, the parametric values would have to be revised and tested again to ensure that the reduced uncertainty provides the desired building performance.

### 5.3.8 Conclusions

The aim of the preceding section was to test the proposed prototype structure on a realistic design problem. It was found that the combinatorial analysis procedure of uncertainty propagation, sensitivity and step-wise regression analysis has the advantage of being able to provide information about the collective impact of the design parameters on the performance metrics. Furthermore, the proposed prototype structure allows a structured approach to the assessment of parameter impact by allowing the simultaneous consideration of multiple parameters.

However, it is necessary to consider intermediate steps such as testing the normality of the distribution of the model output. Furthermore, it is necessary to be aware of the analysis specific requirements, e.g., maintaining the minimum explanatory power of the coefficient of determination.



#### **5.4 Concluding remarks**

The focus of chapter 5 is the conceptual design stage and the meaning of its characteristics for the application of simulation tools. Further, an investigation is conducted into how practitioners use the option space to generate design alternatives.

Finally, the prototype described in 3.4.1 Prototype structure is applied to a realistic design problem. The first part is dedicated to the definition of the design process and design problem. The dedicated research question is: "What are the challenges in conceptual building design related to the use of building performance simulation?". Design problems are "wicked" and as such their solutions require design iterations. The design process is phased. Within the process, the conceptual design stage has some distinctive tasks, such as to explore the option space and to generate and evaluate design concepts. Performance simulation tools have the potential to reduce the impact of design iteration by increasing the speed of the performance evaluations. However, the tools should assist design rather than automate design and support the exploration of the option space by facilitating the rapid generation and evaluation of design alternatives. Ideally, the tool should be adaptable to fit the character of the design stage which it is supposed to support.

The second part investigates the content of the design option space which provides the input for generating design alternatives to be evaluated. The research question addressed was: "What is the extent and content of the option space used by climate engineers and architects to generate integrated design concepts?". The option space is multi-dimensional due to its multi-disciplinary character and participating practitioners interests. The analysis provided empirical evidence of the presence of at least two attributes, four subsystem categories and four relationships. Depending on the experience of the practitioners, components, attributes and relationships are used to a very different extent. Whilst expert designers prefer relationships, novice designers prefer components. Applying the system theory perspective did allow the data to be analyzed from three different sources. The use of parametric attributes for uncertainty and sensitivity analysis is reported in the literature. However, to allow uncertainty propagation and sensitivity analysis to deal with components and relationships, more work is needed on the representation of components. The representation of components can be achieved via a set of fixed attributes which are, to the author's best knowledge, not yet readily available.

The third part of chapter 5 was dedicated to the application of the prototype to a realistic design problem. The research question targeted is: "What are the practical benefits of using BPS-tools extended with uncertainty and sensitivity analysis for conceptual building design?". It was found that the combinatorial analysis procedure of uncertainty propagation, sensitivity and step-wise regression analysis has the advantage of being able to provide information about the collective impact of the design parameters on the performance metrics.

Furthermore, the proposed prototype structure allows a structured approach to the assessment of the parameter impact by simultaneously considering multiple parameters.

However, it is necessary to consider intermediate steps such as testing the normality of the distribution of the model output. Furthermore, it is necessary to be aware of the analysis specific requirements, e.g., maintaining the minimum explanatory power of the coefficient of determination.

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# 6

## Usability in design practice

In the preceding chapters the focus was on formulating tool and process requirements and an analysis procedure. Further, the format of the model input was discussed and tested in application studies. This chapter aims to evaluate the usability of the developed prototype in conceptual building design practice.

The main research question is: “Does the developed prototype fulfill the hypothesis, that uncertainty and sensitivity analysis support conceptual design when integrated with BPS-tools?”

To approach the solution the main research question is decomposed into a number of sub-research questions:

1. How to approach testing the usability of a procedural prototype for climate engineering?
2. Do practitioners see a potential to use techniques for uncertainty propagation and sensitivity analysis in design practice?
3. What usability issues have to be considered for a tool-extension to be successfully used during conceptual design?

### 6.1 Usability engineering

Usability engineering considers usability as the central question in the process of designing software and interfaces. Usability has been a recognized research field since the 1970's and is concerned with improving the interaction of products and users. Studies have been published in different areas such as the design of appliances (Sauer et al., 2010), interactive medical systems (Bastien, 2009), software-, website- and interface design (Folmer and Bosch, 2004, Holzinger, 2005, Nielsen and Landauer, 1993) among others.

Definitions of usability are given by different sources, such as Shackel (2009), Nielsen (1993), ISO9241-11 (1998) and Holzinger (2005). Holzinger defines usability based on work of Bevan (1995) as...

*“...the ease of use and acceptability of a system for a particular class of users carrying out a specific task in a specific environment. Ease of use affects the user's performance and their satisfaction, while acceptability affects whether the product is used.”*

Usability engineering methods and tools are categorized differently by different authors.

Quesenbery (2008) uses four categories: exploratory research, benchmark metrics, diagnostic evaluation and summative testing. Holzinger (2005) differentiates inspection methods (without end-users) and test methods (with end-users).

He subdivides test methods into thinking aloud, field observation and questionnaires, and inspection methods into heuristic evaluation, cognitive walkthroughs and action analysis. Folmer and Bosch (2004) identify usability testing, usability inspection and usability inquiry.

*Usability testing* requires representative users to work with the product on typical tasks. This is accomplished on either a not-yet finished model of the product or on the final product. Testing techniques include thinking aloud and question asking protocols. *Usability inspection* requires either experts, developers or other professionals to assess the ability of a prototype to follow established usability principles. Typical techniques are heuristic analysis and cognitive walkthroughs. *Usability inquiry* is concerned with obtaining information about the likes, dislikes, needs and user understanding of a product in real operation. Information can be gathered by field observations and surveys.

Nielsen (1993) argues that heuristic evaluation is the most common informal method. It is based on usability specialists assessing if the presented product design follows established principles.

Central aspects for conducting usability tests, which are discussed in the following paragraphs, are:

- Type of participants: expert versus novice designer,
- Number of participants: few versus many,
- Prototype fidelity: paper prototype versus fully functional product,
- Choice of heuristics: perspectives and factors.

*Type of participants.* Participants can be chosen based on a number of characteristics such as competence, attitude, state and personality. In the context of this work a competent person is a person who is highly skilled, knowledgeable and able in the domain of climate engineering. Literature provides statements about what type of participant is best suited under the given circumstances. In a recent study Sauer et al. (2010) conclude that when aiming at gaining an overview of usability problems, experts provide a more comprehensive list. If the aim was to identify the most severe usability problems as quickly as possible, novice users would perform better. Severe usability problems are considered problems that would prevent the completion of a specific task. It was found that experts would point to problems relating to efficiency and functionality as they were able to adopt compensating strategies by drawing on previously experienced problems.

In addition to being able to identify actual problems, experts were able to point to potential usability problems

*Prototype fidelity.* The prototype fidelity depends on the stage of the development process. In the late stages fully functional prototypes might be available, whilst this is not the case during the early design stages. The work by Sauer et al. (2010) suggests that subjective usability ratings were unaffected by prototype fidelity. The users seem to be able to compensate for the lack of system and environmental feedback of low fidelity prototypes with their mental model of the product. This compensation occurs as they use their understanding of the product to predict its performance. Low fidelity prototypes are suitable for usability testing taking into account the following three points:

1. Overestimation of available user controls;
2. Limitation of number of measured usability metrics;
3. "Deficiency compensation" might lead to more positive ratings for the low fidelity prototype than the final product.

*Number of users.* Literature gives no clear answer to the question of how many participants to involve. Nielsen and Landauer (1993) propose a model to predict the eventual number of problems that will be found by a usability study. Holzinger (2005) states that inspection methods require 1-5 participants, whilst test methods require 4 to well over-30 participants.

*Choice of heuristic.* The choice of usability heuristics depends on the type of product to evaluate. ISO 9241/11 suggests testing effectiveness, efficiency and satisfaction. Nielsen (1994) proposes nine heuristics for testing Human Computer Interfaces, which are visibility of system status, match between system and real world, user control and freedom, consistency and standards, error prevention, recognition rather than recall, flexibility and efficiency of use, aesthetic and minimalist design, and helping users recognize, diagnose and recover from errors.

## **6.2 Heuristic evaluation of computational prototypes**

Software engineering processes progress to building engineering processes through a number of activities such as project planning, expression of written requirements, provision of a written design, production of code, and documentation of test results. The process is visualized spirally (Braude and Bernstein, 2011).

In response to the perceived "heaviness" of the traditional process, the "Agile Alliance" proposes a more efficient and adaptive development framework.

The main problems addressed are its document driven and static character. The traditional process is only able to cope with changing customer requirements during the development processes.

In the 1990s industry experts started refining process models and subsequently their values and principles. The "Agile Manifesto" was formulated in 2001.

The aim of an agile process is to speed up the product development and to provide means to better accommodate change. The four “agile” process values are (1) Individuals and interactions over process and tools; (2) Working software over comprehensive documentation; (3) Customer collaboration over contract negotiation; (4) Responding to change over following a plan (Bleek and Wolf, 2008).

Similar to the use of design stages in building design, software design is also described using stages such as high-level and detailed design stage. Depending on the size of the project, more stages can be differentiated. During the “high-level” design stage the software architecture is fixed. The detailed design stage produces a product specification for coding. The product specification is typically based on the Unified Modeling Language (UML) and uses case, class, data flow and state models (Braude and Bernstein, 2011).

Publications linking usability engineering to process stages of designing software agree on the significant impact of software architecture on the final product’s usability (Folmer and Bosch, 2004, Juristo et al., 2007). Folmer and Bosch (2004) conclude in their comprehensive review that none of the usability engineering methods such as testing, inspection or inquiry have the capacity to support the definition of the software architecture. However, testing the value of a software concept on feasibility and market acceptance using a paper prototype is considered a valid exercise.

Practitioner’s guides such as those by Dumas and Redish (1999) suggest applying usability engineering techniques throughout the design process from high-level to detailed design. Dumas and Redish (1999) suggest:

1. focusing early and continuously on the user;
2. considering all perspectives to usability;
3. testing versions of the product with users early and continuously;
4. iterating the design according to the feedback.

For the early design stages of software developments they suggest the following:

- Make use of low fidelity prototypes as this allows the rapid turnaround of design iterations.
- Focus on key usability heuristics of the development, which here provide the means to enhance the efficiency of the building design process by providing design guidance.
- Target domain experts as they have the ability to give feedback on the potential of the prototype to increase the process efficiency by adding value and new functionality.

### 6.2.1 Application of heuristic evaluation in practice

For the testing of the usability of the developed computational prototypes, heuristic evaluation was applied using representations of the prototypes on paper, which is a widely used informal usability engineering method (Holzinger, 2005).

Heuristic evaluations were conducted three times following the iterative process of the computational prototype development. 4-6 experts were addressed individually in each iteration. The usability heuristics used targeted the assessment of user satisfaction, efficiency and effectiveness.

User satisfaction, efficiency and effectiveness are defined as (ISO 9241/1):

*User satisfaction:* Freedom from discomfort, and positive attitude towards the use of the product.

*Effectiveness:* Accuracy and completeness with which users achieve goals.

*Efficiency:* Resources expended in relation to the accuracy and completeness with which users achieve goals.

According to the heuristics, criteria are defined such as design support, applicability, computational support and process implementation. The criteria are then tested on specific themes, see Table 6.1.

**Table 6.1 Heuristics, criteria and themes**

Heuristic	Criteria	Theme
Satisfaction	Design support	Usefulness of provided statistic
		Potential to provide design information
		Analysis need in current projects
Effectiveness	Applicability	Use for economic performance assessment of design alternatives
		Use for risk assessment of technical design decisions
		Benefactor of the analysis
		Decision support for selecting the appropriate design alternative.
Efficiency	Process implications	Numeric optimization for conceptual design
		Potential to speed up simulation projects
		Potential to reduce design iterations
		Transparency of analysis process

### *Heuristic evaluation process*

Domain experts were exposed to paper prototypes in the due course of the heuristic evaluation process. The paper prototypes represent the workflow using a BPS-tool expanded with uncertainty propagation and sensitivity analysis techniques on worked-out case studies. The heuristic evaluations were conducted three times, following the iterative development process of the prototype. Two of the evaluations were conducted to obtain an overview and indication of the severity of potential usability problems with regards to the analysis process and design implementation. The third evaluation was conducted to quantify the value of the prototype to support design practice.

First, the experts were exposed to the theoretical background of the prototype. Thereafter, the prototype's capability to provide support in solving a realistic design problem for a representative building was illustrated. Two design alternatives were evaluated. Subsequently, the experts were asked to score the response to key-questions as well as statements making use of a Likert-scale. The audio track of the meetings was recorded to supplement the analysis. The questions were answered anonymously; see Appendix I - Prototype .

The experts were exposed to paper prototypes and engaged in a discussion to obtain their feedback. The individual usability problems were noted and categorized. After completing the prototype evaluation notes were fed back to the experts for information, and where necessary to complement the list of recorded usability problems.

The usability of the final prototype, see Appendix I Final paper prototype, was evaluated in individual sessions with six expert practitioners. To objectively assess the value of the final prototype to support the design process, it was necessary to quantitatively evaluate the cumulative response of the expert practitioners. This was achieved by scaling qualitative feedback. A Likert scale was applied. It allows scaling the expert response to items such as statements, closed- and open-ended questions (Hinkin, 1995). Eleven questions were considered, of which ten are closed- and one is open ended. Mean scores and variances were computed for the closed questions. The maximum number of scores per category was used for the open-ended question. The results from the final prototype evaluation represent the quantitative results.

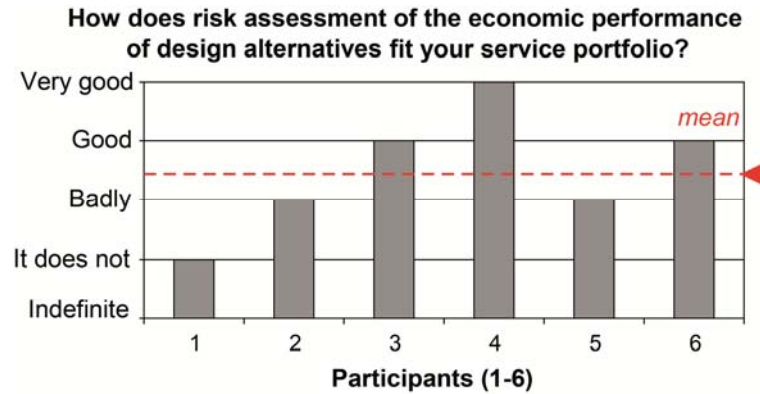
### **6.3 Expert response to prototypes**

In this section the results from the heuristic evaluation are presented. The results are presented in reverse order. The reader will first find the quantitative results followed by the qualitative results.



### 6.3.1 Quantitative heuristic evaluation results

The feedback from the quantitative heuristic prototype evaluation showed different characteristics. It varied over the full range of the scale in some instances, see Figure 6.1, whilst being scattered around the mean of the scale in others.



**Figure 6.1 Application - Risk assessment of economic performance of design alternatives**

The results from the questions are presented in Table 6.2 to Table 6.5. The mean score and variance across the experts' feedback is presented. The mean score gives the cumulative perception of design experts. The variance is used as a metric to evaluate the agreement or disagreement between the experts. Whilst a low variance indicates good agreement, a high variance indicates disagreement.

The experts anticipate that additional design support will be provided by uncertainty propagation and sensitivity analysis. The experts give nearly uniform high scores, see Table 6.2, that:

1. Uncertainty of performance aspects is a useful statistic to support conceptual design.
2. Uncertainty propagation and sensitivity analysis has potential to add value to the design process.
3. Worked on projects would benefit from applying uncertainty propagation and sensitivity analysis.

**Table 6.2 Design support - Results from prototype evaluation**

Pos.	Question	Mean score/ max. score	Variance of scores
1	Is the uncertainty of performance aspects a useful statistic to support conceptual design?	3,5/4	0,3
2	Has uncertainty propagation and sensitivity analysis (UP/SA) the potential to add value to the design process by generating extra design information?	4/4	0,0
3	Would you benefit from applying uncertainty propagation and sensitivity analysis to your current projects?	4/4	0,0

**Note:** Charts presenting the scores of the individual experts can be found in Appendix I - Prototype No charts have been generated for questions 2 and 3 as the expert feedback showed no differences.

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The feedback on the integration of the analysis to the design process varied, see Table 6.3.

1. The collected data does not provide a concluding expert statement with regards to a potentially shortened analysis effort. Whilst two experts score high and very high, two others score low. The data can be interpreted both ways depending on the analysis task at hand.
2. The experts see a high potential of the uncertainty propagation and sensitivity analysis to reduce costly design iterations.
3. As for point 1, no concluding statement is possible with respect to the transparency of the analysis workflow. A contributing factor for the intermediate scores might be the fact that the experts did not see the need to communicate the analysis process to the design team.

**Table 6.3 Process integration – Results from prototype evaluation**

Pos.	Question	Mean score/ max. score	Variance of scores
4	How do you assess the potential of the prototype for UP/SA to reduce time turning over simulation projects?	3,2/5	1,4
5	How do you assess the potential reducing design iterations using UP/SA?	4/5	0,4
6	Is the UP/SA analysis workflow transparent enough to be able to communicate its advantages and disadvantages to the design team?	2,7/4	0,2

**Note:** Charts presenting the scores of the individual experts can be found in Appendix I - Prototype

The feedback on the application of the analysis to address design issues is widely spread, see Table 6.4.

1. The expert opinions vary widely when asked about how the economic risk assessment fits their services. The risk assessment of the economic performance of design alternatives does not seem to be a standard service for the consulted experts. The spread of scores indicates a focus on system design (e.g. sizing) rather than system operation.
2. The experts strongly agree, that the risk assessment of technical design decisions fits their service portfolio.
3. Whilst the practitioners were asked to use a continuous scale for the previous questions, this question makes use of a discrete scale. The discrete scale allows more than one answer per participant. Four participants named the design team as the main benefactor of employing BPS tools extended with uncertainty propagation and sensitivity analysis. Three more stakeholders were named; the client, occupants and the climate engineer. The response of one participant was indefinite as he named all four stakeholders as benefactors.

**Table 6.4 Application – Results from prototype evaluation**

Pos.	Question	Mean score/ max. score	Variance of scores
7	How does risk assessment of the economic performance of design alternatives fit your service portfolio?	2,5/4	1,1
8	How does the risk assessment of technical design decisions fit your service portfolio	3,75/4	0,175
9	Which project stakeholder will benefit most from employing BPS extended with UP/SA?	Design team*	/

\* Discrete choice: Other possibilities were client, occupant, climate engineer or others.

**Note:** Charts presenting the scores of the individual experts can be found in Appendix I - Prototype

Two more questions are dedicated to the need for further computational support. The expert scores on the need for decision support and numeric optimization during concept design are closely scattered, see Table 6.5.

1. The experts agree that additional computational support is useful to select the appropriate design alternatives.
2. Further, they assess the provision of tools for numeric optimization and their application during conceptual design as useful.

**Table 6.5 Computational support– Results from prototype evaluation**

Pos.	Question	Mean score/ max. score	Variance of scores
10	Do you assess extra computational support useful to select the most appropriate design alternative?	3,42/4	0,44
11	Are numeric optimization techniques useful to be applied during conceptual design?	3,67/4	0,27

### 6.3.2 Qualitative heuristic evaluation results

The expert feedback on the prototype presentations was exhaustive. The following motives and issues were identified. First, the points motivating the use of building performance simulation to support conceptual design are listed.

The aim during building design is to match design concepts to user requirements expressed in the form of performance indicators (limits). BPS allows the quantifying of conflicting performance indicators, e.g. energy use and comfort.

Climate engineers have limited influence on the architectural design. Tools that provide useable interfaces, advanced analysis techniques such as uncertainty propagation and sensitivity analysis and intelligent means to present results are expected to significantly improve the communication within the design team, especially between architects and climate engineers.

During design BPS has great potential to shape the expectations of the design team with regards to building performance. Realistic expectations, based on quantitative performance information, help reduce costly design iterations.

The use of performance simulation provides the opportunity to break away from peak performance design and move towards designing for typical performance, e.g. midseason. When aiming at reducing energy consumption for heating and cooling, the integrated system efficiency shows the biggest saving potential.

Subsequently, the following usability issues were addressed by the domain experts.

#### *Prototype application*

Building performance simulation is only used when it supports finding a better design solution or when its results are needed to communicate concept advantages and disadvantages.

The prototype is required to enable an early design robustness assessment for parameters such as user behavior and climate variations. The robustness of the system has consequences on plant, room- and riser sizes.

#### *Variable analysis focus*

*Temporal.* Support the shift in design paradigms: away from peak load towards typical performance design.

*Spatial.* Adaptable analysis zoom-in levels are required to rapidly change focus between workspace, zone and/or building level depended on the considered performance indicator.

*Knowledge access*

Access to knowledge based limits and restrictions for performance indicators and design variables to support definition of parameter input ranges. Decision making and knowledge management systems are expected to be advantageous.

*Representation of analysis input*

The input to analysis tools is ideally of the same type and format as used by practitioners to synthesize integrated design concepts, such as subsystems, components and variables. System theory is expected to provide the required theoretical framework. The dominant type is determined by the design stage, e.g. concept or detailed, and type of project, e.g. new build or refurbishment.

*Extent of component models and parameters*

The minimum requirement for the prototype is to allow the synthesizing of alternative integrated design concepts from components such as: façade, lighting, energy generation and distribution, shading devices, structure and ventilation. The expert's opinions diverge on the required extent of the application. Whilst some statements request extensions to, e.g. model transportation systems in buildings, others advise withdrawing from moving towards all integrated simulation models. The following components are assessed as being particularly important: suspended ceiling and raised floor constructions, displacement ventilation and day lighting systems.

*Modeling detail during design*

The level of modeling detail should be consistent for models targeting early and late design stages. Still, the requirements of the different design stages should be maintained. During concept design the interest lies in evaluating multiple feasible system combinations. Therefore, representative system settings need to be available. During detailed design the aim is to manipulate the system parameters to optimize its integrated performance.

*Design parameter ranges*

Extensions of BPS-tools aiming to support the conceptual design stage should be able to allow an impact assessment of design parameters within realistic ranges such as: ratio net to gross floor area, impact of HVAC systems on aesthetic, HVAC control settings, occupancy pattern, properties of glass, lighting control, convection factor of blinds.

*Performance indicators*

The weight of performance metrics in design decisions is not constant. It changes during the design and construction process.

Examples are given by quotes like: “Costs are not important as long as the budget is not exceeded.”, or “Variations in daylight levels are accepted as long it is not dark.”. To communicate costs and performance, the following metrics are considered: running- , investment- , life cycle- and maintenance costs.

Improving thermal comfort is considered important as it relates to productivity and health. Thermal comfort is particularly crucial in mid-season.

Three metrics are in use to communicate thermal comfort: adaptive temperature limits, overheating hours and weighted overheating hours.

The value of CO<sub>2</sub> emissions to communicate building performance is controversial among the practitioners. Whilst CO<sub>2</sub> emissions might be a performance requirement for public clients, private clients tend to be less considerate.

Practitioner's weigh cost saving potential the highest. That is by improving space use and deliberate investments. The potential for further reductions in energy consumption is assessed as small. When targeting energy efficiency the potential lies in optimized system operation in midseason.

It was suggested to include the occupants' productivity into the cost function. The expectation is that the extra annual income due to higher productivity as a result of better indoor air quality will balance annual depreciation of building and system components.

#### *Analysis process*

Decision making is likely to be supported by an early impact screening of many design (model-input) parameters.

Building design doesn't typically follow prescriptive stages. Design decisions are taken on specific subjects. Those subjects might or might not fall into the timeline of traditional design process descriptions.

To take advantage of uncertainty propagation and sensitivity analysis during the early design stages, practitioners require a two-phased approach. The first phase is an initial qualitative concept comparison, followed by a second, which is a quantitative parameter impact assessment.

#### *Analysis specific result representation*

Experts give little value to the early knowledge of parameter non-linearity's. Knowledge about parameter impact (sensitivity) is assessed as being crucial.

Presentations of results should indicate relationships to easily derive design information. A quote illustrating this need is: “If an engineer cannot explain analysis results, they will be rejected by the design team.”.

#### **6.4 Concluding remarks**

Chapter 6 is dedicated to evaluating the usability of the proposed analysis procedure in conceptual building design practice. The following three research questions were addressed.

1. How to approach testing the usability of a procedural prototype for climate engineering?
2. Do practitioners see a potential to use techniques for uncertainty propagation and sensitivity analysis in design practice?
3. What usability issues have to be considered for a tool-extension to be successfully used during conceptual design?

To answer the questions a number of preparatory initiatives are reported, such as a review of usability engineering and evaluation methods. The final, used method had to be suitable for the early development stage of the computational prototype.

From a methodological perspective it was found that heuristic evaluation best suits the design stage. A paper-prototype, an abstract representation of the computationally implemented analysis procedure's functionality based on a worked out case study, was used for the evaluation. To allow a rapid turnaround of the design iteration, 4-6 domain experts were consulted. During the evaluations heuristics such as user satisfaction, effectiveness and efficiency were addressed. The expert's qualitative feedback was quantified using a Likert-scale.

It was found that the uncertainty of performance aspects was a very useful statistic to support conceptual design and that uncertainty and sensitivity analysis has a high potential to add value to the design process. All six addressed experts stated that they would use the capability if it were available on current projects. Based on the feedback it can be assessed that additionally provided design support is highly satisfactory for the experts.

Effectiveness was addressed using two criteria: applicability and computational support. It was found that the experts would apply the analysis for the risk assessment of technical design decisions. The experts' feedback towards the risk assessment of economic performance of design alternatives was mixed as it is not a traditional service delivered by HVAC-consultants. The value of applying the analysis is anticipated to serve the entire design team. The experts agree that extra computational support during the conceptual design stage is desirable to (1) select the appropriate design alternative and (2) for numeric optimization. Regarding effectiveness, it can be stated that uncertainty propagation and sensitivity analysis is effective only when addressing the core services of the individual organizations. Independent of the services provided, additional services such as optimization and decision support are desired.



Efficiency was tested using questions exploring the design process integration. It was found that the potential of the analysis to reduce design iteration was assessed as very high, whereas the potential to speed up the process of turning over simulation projects was not confirmed. The process transparency was assessed with intermediate to low scores. One participant did not give a vote with the argument "It is not necessary to communicate the analysis process to the design team".

The main research question: "Does the developed prototype fulfill the hypothesis that uncertainty and sensitivity analysis support conceptual design when integrated with BPS-tools?" can be answered positively.

Although the user satisfaction is very high, one needs to account for the limits of the low fidelity prototype, which are the overestimation of available user controls, limited number of usability metrics and "deficiency compensation" leading to a more positive rating.

BPS-tools need to address the core services of the targeted end-user, need to support finding better design solutions and improve communication within the design team. The modeling detail available during the conceptual design stage should be the same as for the detailed design stage. Tools should provide decision support and design optimization.

Finally, it was found that the value of usability engineering is twofold. Firstly, it provides feedback about the usability of the product. Secondly, it allows conveying knowledge, which has the potential to add economic value and/or provide measures to improve the state of the art in design practice.

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# 7

## Overview and conclusions

The final chapter begins with a summary of the accomplished work. The objectives are reviewed and conclusions are drawn. Chapter seven is concluded by providing suggestions for future work.

### 7.1 Overview

The Architecture Engineering and Construction industry has, due to the advances in computing and modeling, arrived in an era of digital empiricism (Paul, 2007). Whilst computational simulation and analysis is employed during the late design stages for compliance checking, it is rarely used during the conceptual design stage. However, the design decisions taken during the early design stages have a significant impact on the final performance of the building. The more complex an integrated building system is, the more difficult it becomes to evaluate its dynamic performance merely based on experience and design guidelines. That is why it is argued in this thesis that performance simulation, when applied early, has the potential to provide design support by providing quantitative performance data that can complement design experience and guidelines. Bästlein (2002) argues that especially complex building projects would benefit from a structured approach to functional and financial risk management. Starting from the current unstructured use of BPS-tools for parameter impact studies, a structured approach is suggested for the evaluation of risk of performance failures early in the design. This thesis addresses five objectives.

1. The first objective was to establish the requirements of BPS-tools to be used in the early design phases. That was achieved by exploring the motivation for using building performance simulation in conceptual design, such as performance based design requirements and prime analysis needs of project stakeholders. Thereafter, the tool capabilities were reviewed. This was done to identify potential discrepancies between needs and existing tool capabilities. The provided list of requirements was then used as input for the development of a tool extension to provide the means for uncertainty propagation and sensitivity analysis. The first objective is addressed in chapter two.
2. The second objective was to identify and evaluate means for facilitating uncertainty propagation and sensitivity analysis to support practitioners in generating and evaluating design alternatives.

To achieve this objective the concepts of risk and uncertainty were reviewed. A literature survey and individual simulation studies were undertaken to identify and test potentially promising techniques for uncertainty propagation. Finally, a prototype was set out and used to test the feasibility of using conceptual design analysis tools and detailed design analysis tools for design support. The second objective is addressed in chapter three.

3. The third objective was to assess the availability, feasibility and validity of data to serve as input for a simulation tool extended with the capability for uncertainty and sensitivity analysis. Two perspectives were distinguished on specification and scenario uncertainties. Scenario uncertainties were differentiated in uncertainties by occupancy and climate. To quantify the uncertainties related to occupancy a literature survey was extended with a survey of an office building in use. To quantify uncertainties related to climate a review of available weather data sets was conducted and complemented with experimental performance simulations. The third objective is addressed in chapter four.

4. The fourth objective was to investigate the characteristics of design problems and processes. Of particular interest was the content and use of the option space which designers use to compose design alternatives. This was accomplished by literature review and data analysis from three different data sources. The data sources were interviews with HVAC consultants, student design activities and realized design projects. The fourth objective is addressed in chapter five. Finally, the application of the prototype is demonstrated on a realistic design problem. The advantages and disadvantages of the prototype are identified.

5. The fifth objective was to test the usability of the prototype in design practice. The objective required a literature survey on usability engineering to identify a suitable evaluation method. Thereafter, usability evaluations were conducted by exposing domain experts to a paper prototype representing an abstract representation of the computational prototype's functionality based on a worked out case study. The expert feedback was quantified with the use of a Likert-scale. The fifth objective is addressed in chapter six.

## **7.2 Conclusions**

The main conclusions drawn are:

There is a noticeable move from prescriptive to performance based design, causing a change of focus from input specification to user requirement. Future regulations will be increasingly performance based. These developments require an even stronger integration of evaluation and design.

Domain experts have a strong focus on design integration and performance communication. Although there is a strong focus on improving the integration of design disciplines, intensifying the use of computational performance evaluation is not a logic conclusion. However, experts focusing on communicating the building performance, increasingly consider the use of computational performance simulation as support tool.

The perception of the design process is not uniformly perceived as a process with clearly defined stages. The process is also perceived as unstructured and iterative. Experts agree that the number of design alternatives developed is higher for complex tasks. It is stated that design teams run the risk of limiting themselves too early to an insufficient number of design alternatives. Design communication has different characteristics during early and late design stages.

The interviewees agree that the use of simulation tools should be facilitated in the beginning of the design process in order to supplement design experience and knowledge when making design decisions.

The available simulation tools are perceived as too detailed to support conceptual design. The required design information necessary to define a building model during the conceptual design stage is not available at the time. Tools for the early design stages must be flexible enough to facilitate expanding the system representations with innovative design concepts. The tools are needed to provide facilities to explore relationships between potential design decisions and performance aspects, enable parametric studies and be able to dynamically scale the model resolution to fit the different levels of information density.

Uncertainty propagation and sensitivity analysis are proposed to provide those capabilities. Simulation environments which quantitatively address uncertainties and sensitivities related to building design and operation are expected to have the potential to (1) provide an indication about the accuracy of the performance predictions; (2) allow the identification of parameters and systems to which performance metrics react sensitively and in-sensitively, respectively; and (3) enable a robustness assessment of design alternatives.

The concept of model based probabilistic uncertainty can be applied to assess the risk of performance failure in conceptual design. A precondition for the concept is the availability of data that describe the range and probability of model input parameters. In case the data is not available, scenario analysis is suggested.

External sampling based procedures are necessary to circumvent the restriction of commercial codes. From those approaches Latin Hypercube sampling coupled with regression analysis has the biggest potential to (1) concurrently provide measures of output uncertainty and sensitivity, (2) account for simultaneous variation of model parameters, (3) handle grouped factors representing subsystems and components, and (4) provide useful input for decision making.

A computational prototype was formulated that acts as a shell, extending commercial tools with a statistical pre- and post- processor. Multiple simulation runs are automatically executed and the results are stored in an output repository. The consideration of abstract tools was abandoned as test results conveyed limited confidence in drawing the appropriate design decision from a set of results. It is recommended to use detailed design analysis tools, with potentially adaptable interfaces, to support the conceptual design stage.

The use of scenarios is common in building design. Design practice makes extensive use of “normative” scenarios to prove compliance with design standards. The use of “exploratory” scenarios is less common. Scenario based load profiles have to meet three characteristics. They have to be: (1) locally representative; (2) up-to date and (3) need to match workplace culture.

Survey results indicate that consulted design guides still provide feasible data. Empirical data confirms the trend towards decreasing equipment gains and the proportional increase in the importance of lighting gains.

In cooperation with VABI BV, future climate data sets were developed using the imposed offset approach. For the first time, exploratory scenarios have been made available for the Netherlands to facilitate the assessment of the future performance robustness of design alternatives.

Testing of the data sets confirmed that neither the original nor the artificial reference data can be used to predict uncertainty ranges for the peak cooling load, a performance metric alien to the statistical selection procedure.

A comparative robustness assessment of three HVAC concepts demonstrated the applicability of the data sets by using the performance metrics annual cooling demand and adaptive temperature limits of 80%.

The “wicked” nature of design problems naturally causes design iterations. Engineering tools, such as building performance simulation models, have the potential to reduce the impact of design iteration by reducing the time needed to evaluate design alternatives.

Within the process the conceptual design stage has some distinctive tasks, such as to explore the option space and to generate and evaluate design concepts.

The option space is multi-dimensional due to its multi-disciplinary character and interests of the participating practitioners. Empirical evidence proves the presence of at least two attributes, four subsystem categories and four relationships. Depending on the experience of the practicing designer, components, attributes and relationships are used to a very different extent. Whilst expert designers prefer relationships, novice designers prefer components.

The combinatorial analysis procedure integrating uncertainty propagation, sensitivity and step-wise regression analysis has the advantage of providing information about the collective impact of the design parameters on the performance metrics. The prototype allows a structured approach to assessing the parameter impact by considering multiple parameters simultaneously.

Heuristic usability evaluation of the prototype confirmed that the uncertainty of performance aspects is an important statistic to support conceptual design. Further uncertainty propagation and sensitivity analysis has a high potential to add value to the design process. The experts' satisfaction with the prototype was high.

Uncertainty propagation and sensitivity analysis is effective when addressing the core services of the individual organizations. Independent of the services provided, additional services such as optimization and decision support are desired.

The potential of the analysis to reduce design iteration was assessed as being very high, indicating a good process efficiency.

Although the user satisfaction is very high, one needs to account for the limits of the low fidelity prototype, which are the overestimation of available user controls, limited number of usability metrics and "deficiency compensation" leading to a more positive rating.

### **7.3 Future challenges**

There is evidence of building regulations developing from prescriptive to performance based, and further to risk based regulations. Risk based regulations will, rather than setting upper and/or lower performance limits, define the building or system performance using descriptive statistics, e.g., a probability distribution function. This is because descriptive statistics and confidence intervals are better able to capture the dynamic system performance as fixed values.

Uncertainty propagation and sensitivity analysis challenge the current approaches to visualize and communicate the results from the data analysis of simulated building models. The current state-of-the-art approaches for performance communication do not appeal to practitioners, nor are they easily comprehensible. Interactive and dynamic approaches are required to communicate the effect of interacting building design parameters and non-linear data sets such as occupancy pattern or weather data sets.

Linking statistical processors to building simulation models for uncertainty propagation and sensitivity analysis requires a significant effort. A vehicle is needed to support the process. The author suggests to test the feasibility of using established formats supporting interoperability such as the IFC file format to support the coupling procedure. The goal is hereby to link analysis variables such as building and system model parameters to alternative values originating from the statistical processor.

One of the major obstacles to facilitating uncertainty propagation and sensitivity analysis is the provision of validated parametric input. It is suggested to bundle efforts and to establish a publicly available data library.

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## **List of Abbreviations**

IBS – Integrated building system

UP – Uncertainty propagation

SA – Sensitivity analysis

CD – Conceptual design

DD – Detailed design

HCI – Human computer interface

CDA – Conceptual design analysis

DDA – Detailed design analysis

TRY – Test reference year

DSY – Design summer year

TMY – Typical meteorological year

KNMI - Royal Netherlands Meteorological Institute

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## Glossary

System parameter	represent system properties. Their combination determines the system response.
Design parameter	describe the physical and/or functional characteristics of a component model with respect to one or more performance metrics.
Domain experts	are very experienced practitioners practicing climate engineering.
Heuristics	are fairly broad usability principle.
Computational prototypes	are computational implementation of an analysis procedure specific for a representative case study.
Paper prototypes	are abstract representation of the computational prototype's functionality based on a worked out case study on paper.
BPS-Tools	are integrated building performance simulation software programs.
Option space	is the pool of alternative components and subsystems that serve as input to compile design alternatives of integrated building systems.
Specification uncertainties	in the context of conceptual building design are uncertainties which arise from incomplete information about the integrated building system under consideration.
Virtual building models	are computational models of a real building or design concept and its exposure to occupancy pattern and external climate. It describes characteristics specific to the analysis need.
Simulation models	are model of physically processes such as heat and mass transfer, and radiation.

Top-cooling	The concept is a widely used conditioning concept in the Netherlands. Air is conditioned centrally and distributed to the rooms. The cooling capacity is used to lower the supply air temperature, maintaining a maximum temperature difference between supply air and external air temperature of typically 10K. The supply air temperature linearly increases if the external air temperature rises above a set point e.g., 28°C. The system does not control the humidity.
Beta-type building	A beta-type building is different to an alpha-type building a building which limits the influence of the user on the indoor thermal conditions. The thermal performance boundaries for beta-type buildings are more stringent than for alpha-type buildings.

**Appendix****Appendix A - Interview data****Table A.7.1 Use of computational tools**

Categories of adopters	Criteria for comp. performance evaluation
Innovators (I)	Compensate shortcomings of existing tools with software developments.
Early adaptors (EA)	Make frequently use of a variety of tools for different analysis tasks and problem resolution levels.
Majority (M)	Occasionally use of a specific performance simulation tool.
Laggards (L)	Don't use tools for design evaluation.

**Table A.7.2 Process integration**

Categories of adopters	Criteria for design integration of disciplines
Innovators (I)	Recognize shortcomings of traditional design process descriptions and propose and test alternative approaches in design practice.
Early adaptors (EA)	Understand the usefulness of integrated design and enhance the interaction with other discipline on demand.
Majority (M)	Accept the defined process structure as is.

**Table A.7.3 Communication**

Categories of adopters	Criteria for performance communication
Innovators (I)	Use new techniques to communicate the performance of design concepts. Aim to influence the design decision employing unconventional techniques.
Early adaptors (EA)	Put high emphasis on the communication of concept performance. Targets the communicating of concept benefits and pitfalls.
Majority (M)	Use standard means for communication.

**Table A.7.4 Practitioners foci in conceptual design**

Interviewee	Computational performance evaluation	Design integration of disciplines	Performance communication
1	I <sup>1</sup>	EA <sup>2</sup>	EA
2	M <sup>3</sup>	EA	M
3	L <sup>4</sup>	M	M
4	M	EA	EA
5	L	I	M
6	L	M	M
7	EA	EA	I
8	M	EA	I
9	M	EA	I
10	EA	M	M
11	I	EA	EA
12	I	EA	EA
13	M	EA	EA
14	I	EA	EA
15	EA	EA	I

The table shows abbreviations I, EA and M relating to Rogers (2003) categories of adopters of innovation. I<sup>1</sup> Innovator; EA<sup>2</sup> Early adaptors; M<sup>3</sup> Majority; L<sup>4</sup> Laggard.



## Appendix B – Software & Examples

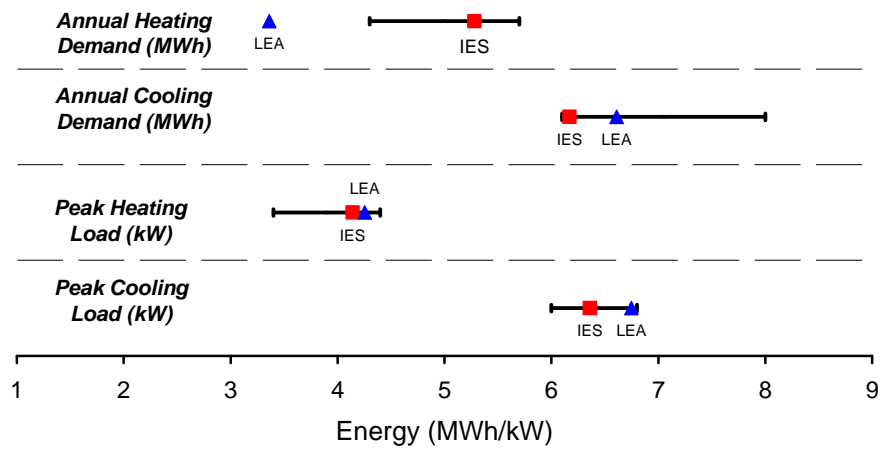
### Tool selection

**Table B.7.1 Bestest Case 600 - Material properties and assigned standard deviations**

		Thickness	Standard deviation	Conductivity	Standard deviation <sup>[1]</sup>
Units		(m)	(m)	(W/mK)	(W/mK)
Wall	Plasterboard	0,012	/	0,16	0,04
	Fiberglas quilt	0,066	0,02 <sup>[2]</sup>	0,04	0,016
	Wood siding	0,009	/	0,14	0,015
Floor	Timber flooring	0,025	/	0,14	0,0378
	Insulation	1,003	/	0,04	0,016
Roof	Plasterboard	0,010	/	0,16	0,04
	Fiberglas quilt	0,1118	0,02 <sup>[‡]</sup>	0,04	0,016
	Roof deck	0,019	/	0,14	0,0238

<sup>1</sup> The standard deviations for the different material and thermo physical properties were calculated based on published data from Clarke et al. (1991),

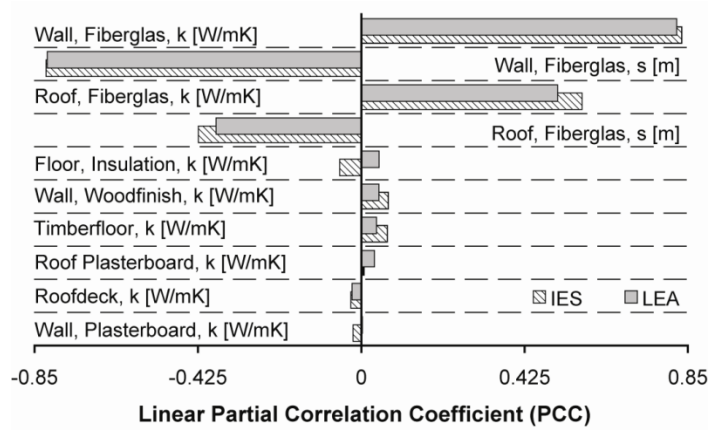
<sup>2</sup> or were derived from De Wit (2001).



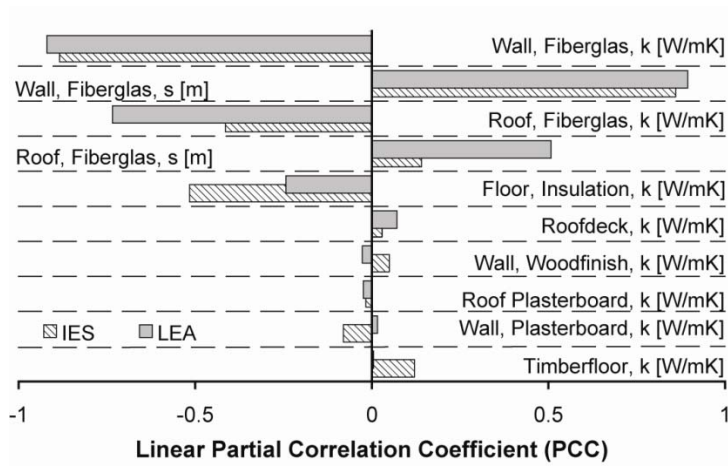
**Figure B.7.1 Bestest Case 600 Results, Comparison IES – LEA.**

**Table B.7.2 Bestest Case 600 – Aggregated material properties and standard deviation**

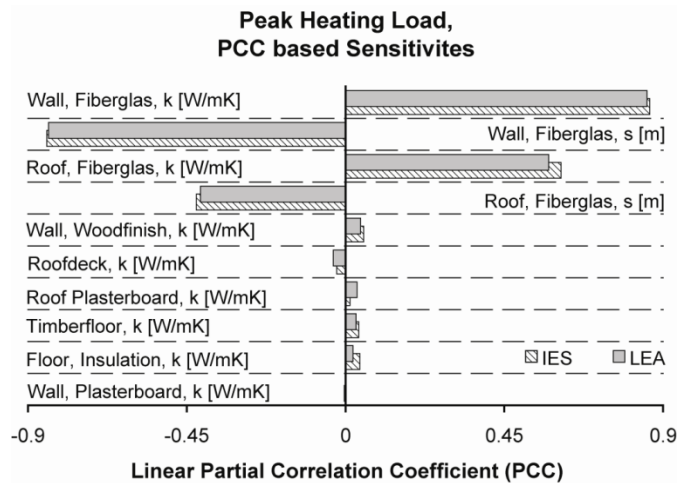
	Thermal Resistance (m <sup>2</sup> K/W)	Standard deviation (m <sup>2</sup> K/W)
Wall	1.79	2.04
Floor	25.25	21.98
Roof	2.99	3.78



**Figure B.7.2 Annual energy demand for heating, PCC based sensitivities, Comparison IES and LEA**



**Figure B.7.3 Annual energy demand for cooling, PCC based sensitivities, Comparison IES and LEA**



**Figure B.7.4 Peak Heating Load, PCC based Sensitivites, Comparison IES and LEA**

### Differential sensitivity analysis

**Table B 7.5: Differential sensitivity analysis - parameter ranges.**

Parameter	Unit	Max.	Reference	Min.	Comment
Office/gross floor area	[%]	79	67	55	/
Window to wall ratio	[%]	70	60	50	/
Room height	[m]	4	3.7	3.4	Floor to floor
g-value	n/a	0.6	0.35	0.23	Pilkington (Pilkington, 2011)
U-value glass	[W/m <sup>2</sup> K]	1.0	0.75	0.5	/
U-value façade	[W/m <sup>2</sup> K]	0.3	0.2	0.1	/
Orientation	[Degree cw]	90O	45O	0O	North to south
Infiltration	[1/h]	0.25	0.2	0.15	Element 29
Thermal active masse	/	high	moderate	Low	/
Internal gains	[W/m <sup>2</sup> ]	50	32	14	SIA MB 2024

**Morris analysis****Table B 7.6 Parameter and range**

Pos.	Parameter	Unit	Range
1	Glass to wall ratio	[%]	25-85
2	g-value	[-]	0.3-0.7
3	U-value window	[W/m <sup>2</sup> K]	1.1-1.8
4	U-value external wall	[W/m <sup>2</sup> K]	0.2-0.5
5	Internal gains <sup>1</sup>	[W]	265-970
6	Ventilation rate <sup>2</sup>	[m <sup>3</sup> /h]	91-160
7	Orientation	[deg]	1-360
8	Air change rate	[1/h]	0.12-0.25
9	Thermal mass	[-]	high, medium, low
10	Louvre control <sup>3</sup>	[W/m <sup>2</sup> ]	250-600

**Parameter distribution:** All parameter but thermal mass are distributed uniform. Thermal mass is distributed discreet.

<sup>1</sup> Sensible heat gains from equipment and people.

<sup>2</sup> Based on fresh air rates for an office occupied by two.

<sup>3</sup> Set point to close internal louvers is based on the solar gains on façade.

**Table B 7.7: Morris analysis – samples for trajectory 1 and 2.**

Parameter	Nr.	1	2	3	4	5	6	7	8	9	10
Name	Glass to wall	g-value	U-Window	U-Wall	Int. gains	Vent. rate	Orient.	ACH	Mass	Louvres setpoints	
Range	25-85	0.3-0.7	1.1-1.8	0.2-0.5	265-970	91-160	1-360	0.12-0.25	1,2,3	250-600	
Samples	1	80	0.33	1.39	0.37	793.75	142.75	90.75	0.20	2	512.5
Trajectory 1	2	80	0.33	1.39	0.37	793.75	142.75	90.75	0.13	2	512.5
	3	80	0.33	1.39	0.37	793.75	142.75	90.75	0.13	2	337.5
	4	80	0.33	1.74	0.37	793.75	142.75	90.75	0.13	2	337.5
	5	80	0.33	1.74	0.23	793.75	142.75	90.75	0.13	2	337.5
	6	80	0.33	1.74	0.23	793.75	142.75	270.25	0.13	2	337.5
	7	80	0.33	1.74	0.23	441.25	142.75	270.25	0.13	2	337.5
	8	80	0.33	1.74	0.23	441.25	142.75	270.25	0.13	3	337.5
	9	80	0.53	1.74	0.23	441.25	142.75	270.25	0.13	3	337.5
	10	80	0.53	1.74	0.23	441.25	108.25	270.25	0.13	3	337.5
	11	50	0.53	1.74	0.23	441.25	108.25	270.25	0.13	3	337.5
	12	70	0.6	1.39	0.28	911.25	108.25	90.75	0.13	2	570.8
Trajectory 2	13	40	0.6	1.39	0.28	911.25	108.25	90.75	0.13	2	570.8
	14	40	0.6	1.39	0.28	911.25	108.25	90.75	0.13	2	395.8
	15	40	0.6	1.39	0.28	911.25	108.25	90.75	0.13	3	395.8
	16	40	0.6	1.74	0.28	911.25	108.25	90.75	0.13	3	395.8
	17	40	0.6	1.74	0.28	911.25	108.25	270.25	0.13	3	395.8
	18	40	0.4	1.74	0.28	911.25	108.25	270.25	0.13	3	395.8
	19	40	0.4	1.74	0.28	558.75	108.25	270.25	0.13	3	395.8
	20	40	0.4	1.74	0.28	558.75	142.75	270.25	0.13	3	395.8
	21	40	0.4	1.74	0.43	558.75	142.75	270.25	0.13	3	395.8
	22	40	0.4	1.74	0.43	558.75	142.75	270.25	0.20	3	395.8

### **Tool overview**

**Orca** v1.0 is a commercial development of a new interface to the calculation engine VA114, by TNO. VA114 is a calculation engine dedicated to assess the overheating risk in buildings and forms part of VABI's Uniform Environment. The uniform environment is a software tool box that allows exchanging virtual building representations between several tools for different types of analysis including heat loss and heat gain calculation. The intention is to optimize the thermal comfort and reduce energy use. ORCA was developed as part of the research program "Meta Design Environment" at the Technical University of Delft, Faculty of Architecture.

**Henk** (Het Energie Neutrale Kantoor) v3.0 is a commercial energy calculation tool explicitly developed for the early design stages. It was intended to be used for communicating engineering concepts between engineers and architects. It is easy to use and should be used in one to one sessions to answer design questions immediately and to guide the design process.

**Building design advisor** v3.1 (beta) is a free of charge, stand-alone integrated design tool. BDA claims to be most effectively used from the initial design to specific system definition. The tool is supposed to act as data manager and process controller for the three calculation modules; DCM (day lighting computation module), ECM (Electric lighting computation module), DOE2 (Energy analysis module). Results from parametric studies can be directly compared on screen.

**MIT Design advisor** v1.0 is a free of charge on-line façade design tool for architects and building engineers. This tool has been developed to give preliminary estimates for the performance of building facades. Double skin facades may be compared to conventional facades, and location, occupancy and depth of the perimeter space may be adjusted and the effects viewed.

**Energy 10** v1.2 is a commercial conceptual design tool. It focuses on facilitating trade-offs studies during early design phases for buildings with less than 10,000 ft<sup>2</sup> floor area or buildings that can be treated as one or two-zone increments. It performs whole-building annual energy analysis, including dynamic thermal and day lighting calculations. It is specifically designed to facilitate the evaluation of energy-efficient building features in the very early stages of the design process.

**eQuest** v3.5 is a freeware building energy use analysis tool, which produces results with an affordable level of effort. eQUEST was designed to perform analysis of building designs and technologies by applying building energy use simulation techniques. The tool makes use of the DOE2 calculation engine. Model building is supported by wizards. The detailed input information about building construction and HVAC system configurations can be assigned by default. The results include life cycle costs and code compliance analysis as well as energy demand and consumptions. The baseline design can be compared with different options.

**Low Energy Architecture (LEA) v0.9.1 (beta)** Is the successor of h.e.n.k.. Its calculations are based on a fully explicit discretization scheme. It is using a forward difference method with a time-step of two minutes. The tool was specifically developed for Dutch professionals to predict instantaneous peak loads and annual energy demands during the early design stages. Because it is meant to support early phase design, LEA reduces the representation of a building and its operation to the most crucial input variables. As an example, the building is modeled as one thermal zone and walls are defined by thermal resistances only. For simplicity the tool makes use of the assumption of an isothermal wall ( $B_j < 0.1$ ). Another simplification is that only the floor and ceiling are defined as being thermally active. Different to the walls the floor/ ceiling construction is spatially discretized. Depending on the defined thermal mass of its construction a number of nodes are defined governing its dynamic thermal response. The thermal energy stored in the structure is equally distributed over floor and ceiling. Their thermal response is defined by the internal convection coefficient. The used prerelease works without user interface, using XML input and output file. Internal and external gains are pre-calculated for every hour in advance (Zoon, 2008).

**IES Virtual Environment v5.5** uses the ApacheSim for dynamic simulations. A discretization scheme called "hopscotch" which is similar to the Crank-Nicholson scheme is applied. This discretization scheme applies explicit and implicit time-stepping to alternate nodes of the construction. The advantages of this method are a high level of accuracy combined with very efficient computation. IES VE is a detailed integrated building performance simulation tool addressing professionals worldwide. Its modular structure integrates features to predict building energy use and peak loads. The modules cover capabilities as lighting simulation, shadow cast, value engineering, life cycle costing, evacuation, component sizing and environmental CFD. The program is suited for design evaluation of buildings and systems, and provides an environment that enables the user to address a multitude of performance indicators, e.g., energy use, thermal comfort and daylight availability.

**VA114** is based on Fourier equations which are solved using a total implicit differentiation method. VA114 is a detailed integrated building performance simulation tool for the early design stages. It is an industry-strength and extensively used tool in the Netherlands. The tool is dedicated to the analysis of building energy use and thermal comfort. It represents one of twenty modules in a toolbox called VABI Uniform environment. The toolbox includes tools for sizing building services components and systems, calculating heat gains and losses as well as assessing cold bridging. The results are stored and saved in text files. A separate tool, Uitvoerviz, is dedicated to the graphical presentation results.

**HAMBASE** (Heat Air and Moisture Building and Systems model) is a simulation model for heat and vapor flows in a building. With the model the indoor temperature, the indoor air humidity and energy use for heating and cooling of a multi-zone building can be simulated. A first version of this model (ELAN) was published in 1987 (De Wit and Driessen, 1988).



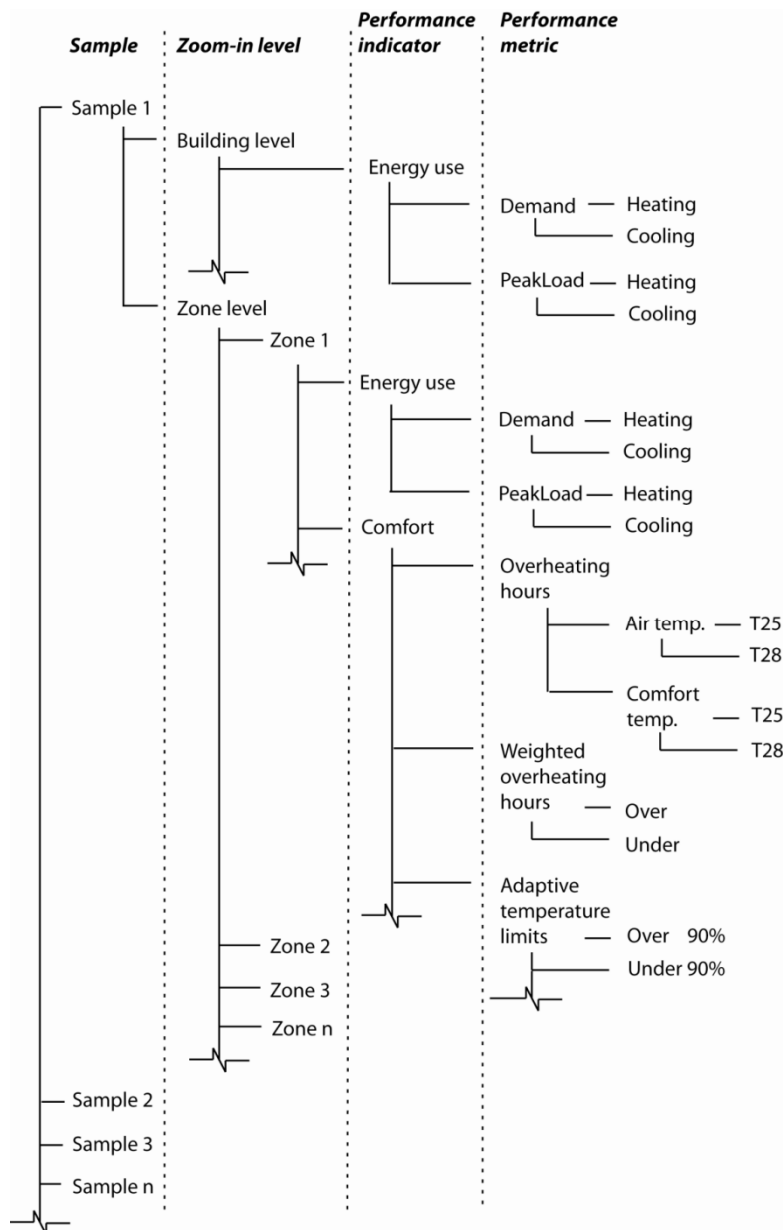
Ever since, the model is continuously improved and expanded, i.e. integrating a model for predicting the indoor air humidity (Schijndel and de Wit, 1999) (Wit, 2006). The models are available under public domain licensing from the HAMLab website.

**Simlab v2.2 & v3.2** Simlab is a tool to learn use and exploit sampling based uncertainty and sensitivity analysis. It consists of features for model data pre-processing and post-processing. The model can be defined internally or externally. Whilst Simla v2.2 is a stand-alone software tool with user interface, all later releases are distributed in binary format. It supports environments as C, C++, Matlab and Fortran (Saltelli et al., 2004).

**Matlab R2007a** Matlab (Matrix Laboratory) is commercial platform-independent software numerical computing. It provides an interactive environment and access to a multitude of toolboxes for engineering and science. It covers functions for linear algebra, statistics, Fourier analysis, filtering, optimization and numerical integration.

**Appendix C - Computational prototype**

**Visual representation of output repository**



**Figure C.7.1 Prototype output repository - Example**

**Appendix D - “BETA-Building” description**

The “BETA-building” is a four storey high office building with two wings, A and B, connected by an atrium, see Figure 4.1 “BETA-building”, 4th floor - plan view. As the Beta-building was not fully occupied at the time the work focused on the top-floor offices of the building<sup>1</sup>. The office layout shows a mix of open-plan and cellular offices spaces, meeting rooms, a reception area with access to toilets and a hot drinks vending machine. Each wing houses one office unit. The BETA-building is equipped with a central ventilation system with pre-heating maintaining a minimum fresh air supply temperature of 18°C. The occupied office units are equipped with fan coil units for heating and cooling. The installed cooling capacity is limited to 25W/m<sup>2</sup>. The buildings heating system is served by district heating.

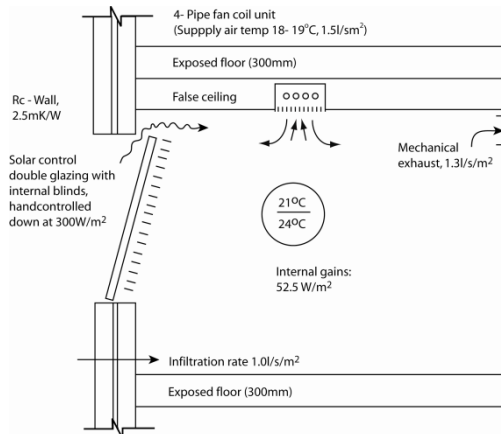
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<sup>1</sup> The top-floor is occupied by ARUP BV. an international multidisciplinary engineering consultancy.

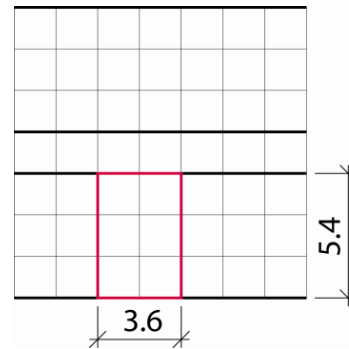
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### Appendix E - Climate data applicability: Case study

The case study represents a standard, integrated building and system, office concept. The space is ventilated making use of a hybrid ventilation scheme. The air is naturally supplied and mechanically extracted. Heating and cooling is provided making by 4-pipe fan coil unit with heating set point at 21°C and cooling set point at 24°C. The space is occupied by two people from 8:00 to 18:00 hours. Figure 1 and 2 show the conditioning concept and office location, respectively.



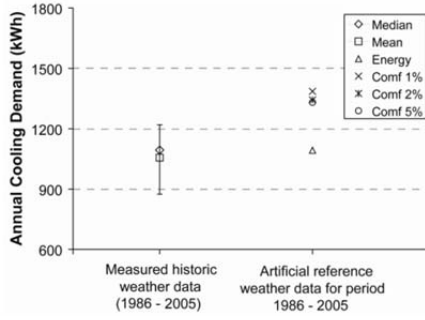
**Figure E.7.2 Office conditioning concept – Standard**



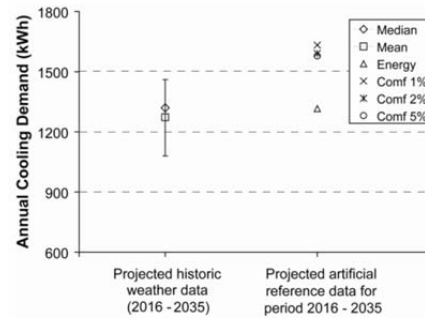
**Figure E.7.3 Floor plan and architectural grid**

The results for the annual cooling demand show a good agreement between the median of the measured and projected historic data sets and derived artificial reference data set for energy predictions. The observation confirms the expectation that the artificial reference file for energy consumption simulations is well suited to represent the reference period.

When using the artificial reference years to predict the annual cooling demand two things can be noticed. First, the most extreme data set 1% predicts the highest cooling demand and the least extreme the lowest. That indicates that the annual cooling demand of the case study is indeed dominated by the weather parameter dry bulb temperature. Secondly it can be noticed that the artificial reference files for the comfort assessment lead to overestimation of the cooling demand for the case study of 11% and 9.5%.



**Figure E.7.4 Annual cooling demand; from 20 measured historic weather data sets - distribution indicated by mean, median, 5th and 95th percentiles; and from 4 artificial reference weather data.**



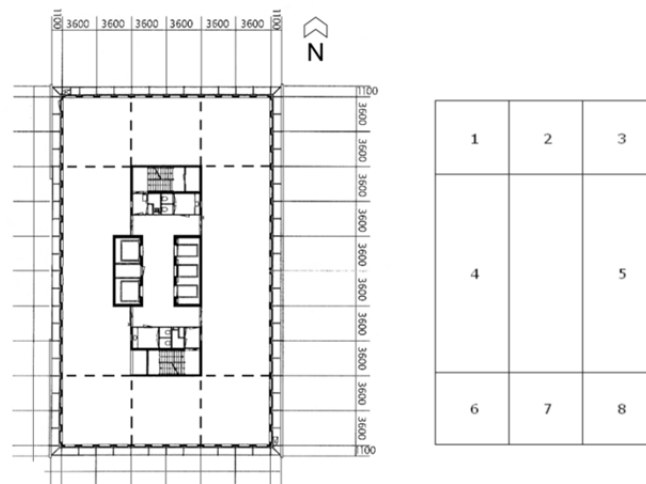
**Figure E.7.5 Annual cooling demand; from 20 projected historic weather data sets (KNMI W+ scenario) - distribution indicated by mean, median, 5th and 95th percentiles; and from 4 projected artificial reference weather data.**

## Appendix F - Robustness assessment of HVAC-concepts

### Case description

The case study considers one intermediate floor of the office building 'La tour' in Apeldoorn. The building consists of flexible office floors with a central core (see figure 2). The building is conditioned with a top-cooling concept. The space around the core is divided in corner offices and façade offices. Assembly rooms and circulation spaces doors are neglected to keep the model as simple.

The core is enclosed with a concrete wall of 200 mm. The corner and facade offices are separated by light-weight system walls. The façade has a glazing percentage of 27%, with an overall solar transmittance of 0.30 (g-value). The East, South and West façades are equipped with overhangs. During office hours the offices are maintained on 20°C and the core on 18°C.



**Figure F.7.6** Floor plan of intermediate floor plan of the "La tour" office tower and its virtual representation for the performance predictions.

### HVAC-concept alternatives

The presented simulation study only considered the summer period. That is why heating installation is not represented. The consideration of the system performance and its control in winter and mid-season is not considered.

*Top cooling* concept is a widely used conditioning concept in the Netherlands. Air is conditioned centrally and distributed over the floors to the rooms. The top-cooling capacity is used to lower the supply air temperature. It does not control the humidity.

The supply air temperature is 18°C. However the supply air temperature linearly increases if the external air temperature rises above 28°C. The system maintains a maximum temperature difference between supply air and external air temperature of 10K. The system is expected to be critical with respect to climate change.

The second conditioning concept is *floor-cooling*. The system makes use of pipework installed within the top layer of flooring. Conditioned water is pumped through the pipes to temperate the floor as heat exchanger. The system is modeled to continuously maintain a water temperature of 17°C for cooling and 35°C for heating.

The moderate temperatures are advantageous as they result in lower distribution losses and allow the use of heat pumps and heat and cold storage. The disadvantages are high inertia of the system resulting in a slow thermal response to instantaneous environmental changes. As only the cooling season is considered the heating capacity is set to zero. Fresh air is provided centrally but unconditioned at the minimum flow rate.

The last conditioning concept considered is the *traditional local air-conditioning* via 4-pipe fan coils. The fan coil uses convection to via preconditioned air to heat and cool the space. Different to a 2-pipe the 4-pipe fan coil has different set of supply and return pipes for heating and cooling. The supply water temperature for cooling is 6°C. Heating is not modeled. Its capacity is set to zero. Fresh air is provided centrally but unconditioned at the minimum flow rate.

---

**Appendix G - Option space, observation checklist and data**
**Table G.7.8 Checklist for observation of student design team observation**

Pos.	System elements
1	building position
2	orientation
3	access points
4	number of storey
5	load-bearing structure
6	thermal mass
7	floor size
8	room size
9	internal access routes
10	type of facade
11	façade materials
12	infiltration and air tightness
13	wall-window relation
14	window and door position
15	U-value, g-value, light transmission
16	wall material and thickness
17	roof material and thickness
18	floor material and thickness
19	color scheme
20	finishes
21	heating/cooling plant
22	end-equipment in rooms
23	artificial lighting
24	day lighting
25	occupancy scheme, internal gains
26	air change rate
27	HVAC system parameters
28	size of plant room
29	location of plant room (plus “non-predefined parameters” introduced by design team)

---



**Table G.7.9 Attribute emergence and consideration of components and relationships for a student project, week 1 to 3.**

Week:	Attributes:	Components:	Relationships:
1	Building volume (crude) Site lay-out + Urban context	Structure (high-rise) Rooms (volumes in general lay-out) Room zones (Topology in architectural layout/ internal organization) On site services	Building and environment, (indicated by: passive solar heating energy use and architectural esthetic – organization)
2	Building massing (4 to 5 storey) Glazing percentage (high for labs)	Facilities (Rooftop restaurant) Green roof (sedum) Structure (steel or timber frame)	None
3	Orientation Building massing (8 storey) Glazing percentage (window-wall ratio 50%)	Structure (pre-cast concrete frame with gluelam roof beam) Facade (aluminum system)	Building and occupants, (indicated by: air flow/ comfort and day lighting)

**Table G.7.10 Attribute emergence and consideration of components and relationships for one real-life project.**

	Attributes	Components	Relationships
Rijnland Office, Leiden	Building mass	Long term thermal storage system	Building and environment (indicated by enforcing compliance with building regulations and energy performance coefficient)
	Functional zoning/ space use	Heat pump  Low temp heating system  High temp cooling system  Atrium  Climate façade	Building and owner, (indicated by budget)

**Table G.7.11 Attribute emergence and consideration of components and relationships from interviews with 3 design practitioners.**

Interviewee	Attributes	Components	Relationships
1	Location of building	Façade	Building and environment (indicated by considering exposure to noise, wind, sun)
	Massing of envelope	Building services	
	Orientation		
2		Building services	
		Structure	
		Form/ Orientation	
3	Properties of glass	Window systems	Building and environment (indicated by considering peak loads, night cooling potential)
	Orientation	Wall systems	Building and occupants(indicated by considering internal air flow and daylight availability)
	Thermal capacity of structure	Building services	
	Percentage glass		
	Shading coefficient		

---

**Appendix H - Prototype application**

**Table H.7.12 Design Alternative 1 - Coefficients of performance**

	Heating (Heat pump, electric)	Cooling (Compression chiller, electric)
Generation	5	4
Distribution	0.85	0.9
Total	4.25	3.6

**Table H.7.13 Design Alternative 2 - Coefficients of performance**

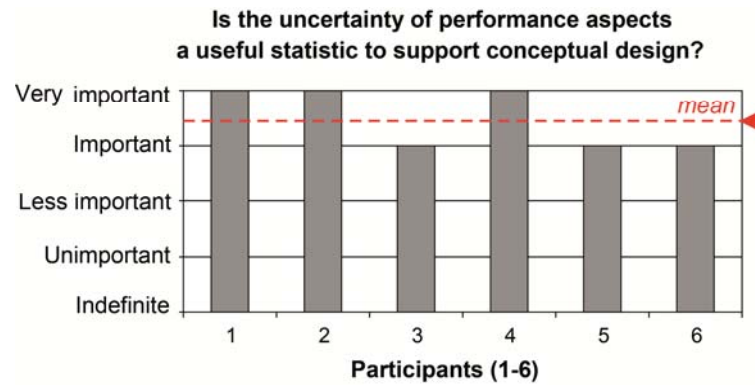
	Heating (High efficiency boiler, gas fired)	Cooling (Compression chiller, electric)
Generation	0.92	4
Distribution	0.9	0.9
Total	0.828	3.6

**Table H.7.14 Descriptive statistics for model output**

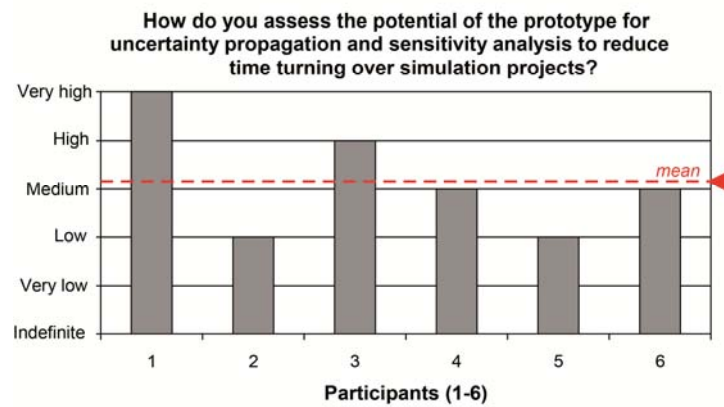
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	Final energy		h > ATL 80% Beta	
	DA 1	DA 2	DA 1	DA 2
Mean	6220.4	18601.1	339.2	35.9
Standard error	65.9	187.8	46.2	10.1
Median	6147.0	18600.2	135.5	0.0
Standard dev.	659.4	1877.5	462.0	100.6
Variance	434820.8	3525073.1	213485.9	10118.8
Kurtosis	-0.8	-0.2	0.9	34.8
Skew	0.2	0.1	1.5	5.3
Minimum	5045.1	13757.7	0.0	0.0
Maximum	7698.0	23102.9	1586.0	793.0
Sum	622038.7	1860105.3	33919.0	3593.0

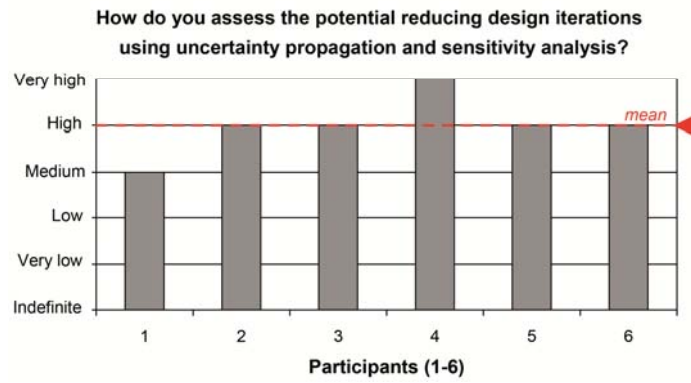
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**Appendix I - Prototype usability**

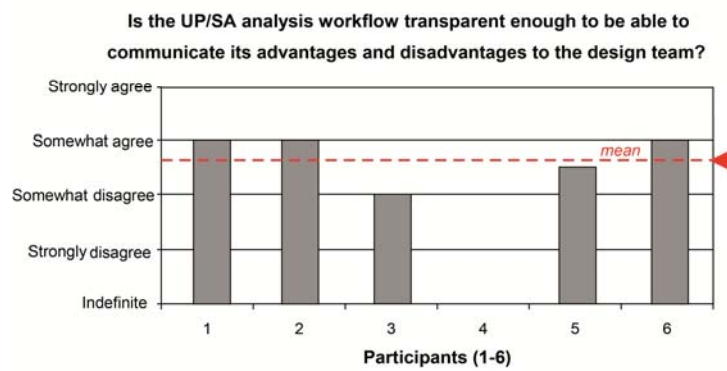
**Figure I.7.7 Design support – Usefulness of parameter uncertainty as statistic to support concept design**



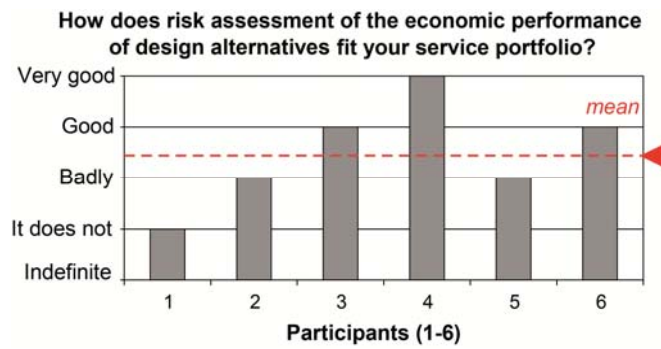
**Figure I.7.8 Process integration – Potential to reduce time turning over simulation projects**



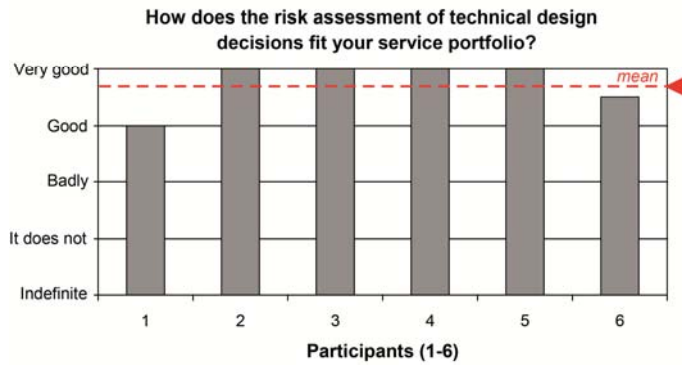
**Figure I.7.9 Process integration – Potential to reduce design iterations**



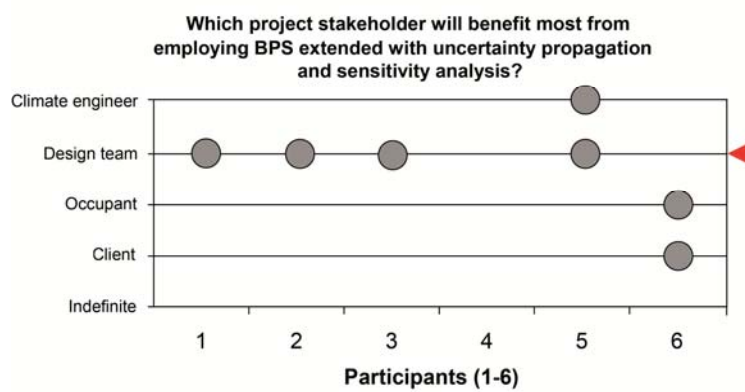
**Figure I. 7.10 Process integration – Transparency of analysis workflow**



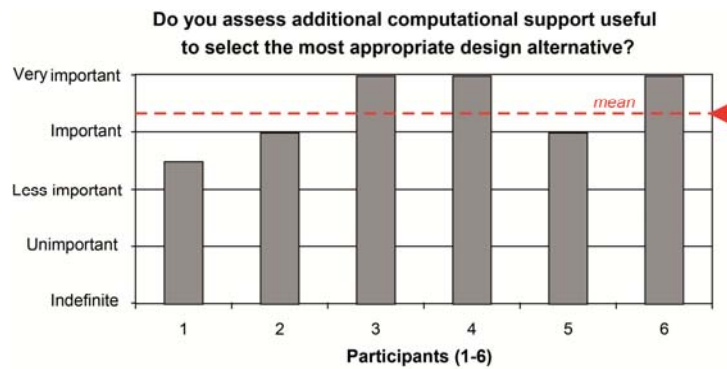
**Figure I.7.11 Application – Risk assessment for economic performance of design alternatives**



**Figure I.7.12 Application – Risk assessment of technical design decisions**



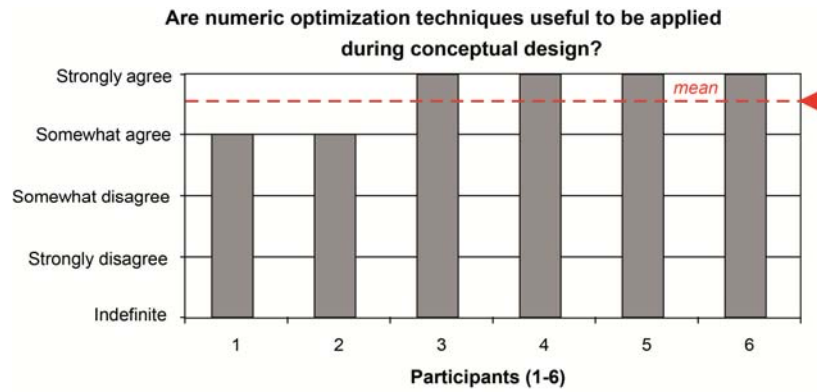
**Figure I.7.13 Application – Anticipated beneficial project stakeholders**



**Figure I.7.14 Computational support – Selection of appropriate design**



*alternative*



**Figure I.7.15 Computational support – Application of numeric optimization for concept design**

**Final paper prototype**

Slide 1

1

**Usability of Uncertainty Propagation and Sensitivity Analysis for Conceptual Design**

**Part 1: Background**

*Part 2: Application*


*Part 3: Questions*

## Slide 2

2

### User testing

*Does the developed prototype fulfil the hypothesis, that uncertainty and sensitivity analysis support conceptual design when integrated with BPS - tools?*



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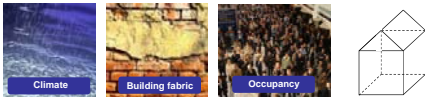
## Slide 3

3

### Early use of BPS-tools

Aspects related to evaluating design alternatives:

1. *Confidence in simulation results;*  
(e.g., indication of output accuracy)
2. *Robustness to future climate and occupancy scenarios;*  
(e.g., performance failure risk assessment)
3. *Provision of design guidance.*  
(e.g., performance graphs)



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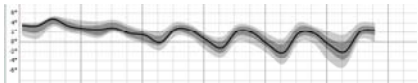
## Slide 4

4

### Uncertainties

Problem:

1. *Simulated building performance differs in most cases from measured building performance!*
2. *Uncertainty analysis is integral part analysing measured data but NOT analysing computationally simulated data!*




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Slide 5

5

**Potential of BPS-tools with UP&SA**

To provide quantitative data to complement design experience,  
*...accounting for interaction of physical phenomena, and  
...allowing simultaneous representation of continuous and  
discrete variables.*



(Adapted from ISSO 300,1994, Thermally active building mass; J.J.L.F. low, medium, high)

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Slide 6

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Part 1: Background

**Part 2:**  
**Example application study**

Part 3: Questions

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Slide 7

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**Realistic design problem**

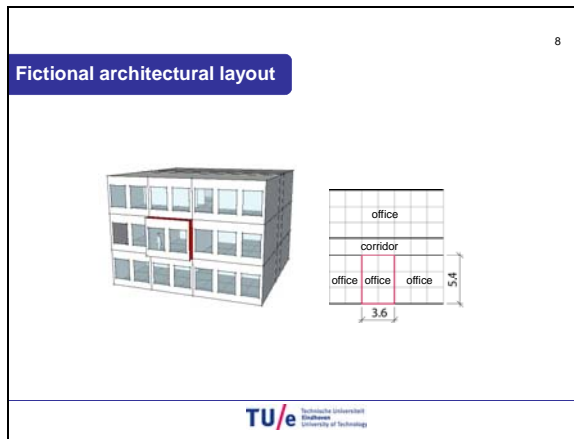
Identify a design alternative which represents the most appropriate compromise for the conflicting client requirements:

1. Good thermal comfort at workplace level;
2. Low final energy demand for heating and cooling at building level;
3. Pleasing (aesthetic) design;
4. Design and planning to budget.

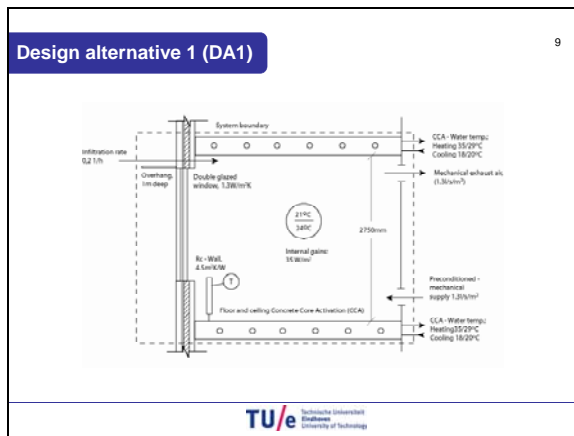


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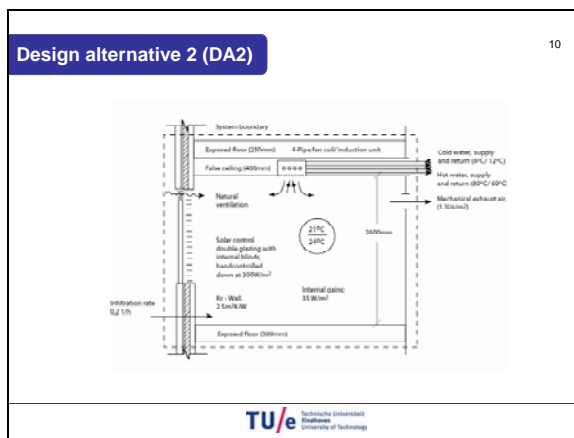
Slide 8



Slide 9



Slide 10



Slide 11

11

### Design parameter ranges

*(Parameters, component combinations and control set points)*

Pos.	System	Architectural	Design	Unit	Min.	Max.	DA1	DA2
		Subsystem levels	parameter					
1	Building	Building/Room	Orientation	[deg]	1	360	x	x
2	Façade	Building/Room	g-value (zta)	[n/a]	0.3	0.7	x	x
3	Façade	Building/Room	U-value fenestration	[W/m <sup>2</sup> K]	1.1	1.8	x	x
4	Façade	Building/Room	U-value external wall	[W/m <sup>2</sup> K]	0.2	0.5	x	x
5	Façade	Building/Room	Internal blinds, control	[W/m <sup>2</sup> ]	250	600	n/a	x
6	Façade	Building/Room	Infiltration rate	[1/h]	0.15	0.25	x	x
7	Façade	Room	Glass to wall ratio	[n/a]	0.25	0.85	x	x
8	Services/HVAC	Room	Ratio acoustic to active ceiling	[n/a]	0.15	0.7	x	n/a
9	HVAC	Room	Ventilation rate	[m <sup>3</sup> /h]	91	160	x	x
10	Structure	Room	Thermal active mass	[n/a]	low	high	high	x
11	Interior	Room	Internal gains, equipment + people	[W/m <sup>2</sup> K]	14	50	x	x
12	Services/Lighting	Building/Room	Light fittings control	[lux]	400	600	x	x

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Slide 12

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### Final energy use

#### Coefficients of performance

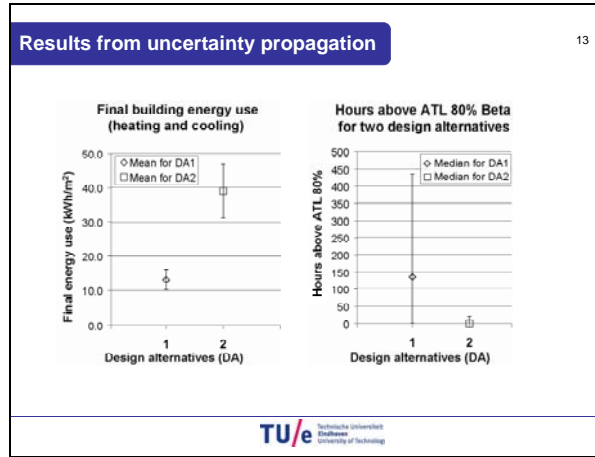
DA1	Heating	Cooling
	Heat pump (electric)	Compression chiller (electric)
Generation	5	4
Distribution	0.85	0.9
Total	4.25	3.6

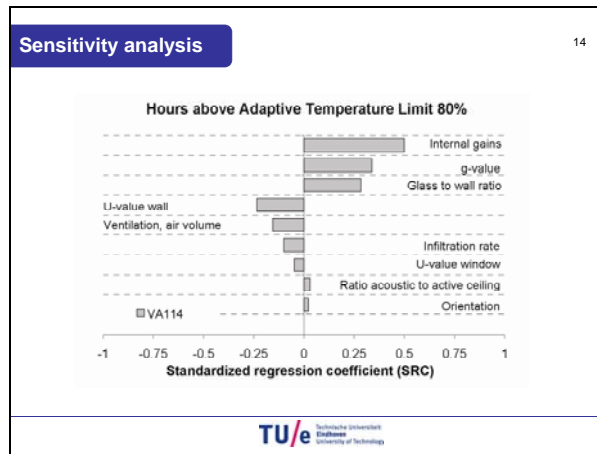
DA2	Boiler (HR ketel) (gas)	Compression chiller (electric)
	Generation	0.92
Distribution	0.9	0.9
Total	0.828	3.6

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Slide 13



Slide 14



Slide 15

**Stepwise regression analysis** 15

Step <sup>(a)</sup>	Parameters <sup>(b)</sup>	SRC <sup>(c)</sup>	R <sup>2</sup> <sup>(d)</sup>	R <sup>2</sup> in % <sup>(e)</sup>
1	Internal gains	0.499	0.309	49.7
2	g-value	0.338	0.446	71.7
3	Glass to wall ratio	0.283	0.530	85.3
4	U-value external wall	-0.235	0.584	93.9
5	Ventilation rate	-0.154	0.609	98.0

<sup>(a)</sup> Steps in forward-stepwise regression analysis.  
<sup>(b)</sup> Variables listed in the order of selection in regression analysis.  
<sup>(c)</sup> SRC's for parameters in final regression model.  
<sup>(d)</sup> Cumulative R<sup>2</sup> value for each parameter entry to regression model.  
<sup>(e)</sup> Cumulative contribution in % for each parameter entry on final R<sup>2</sup>.

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*Part 1: Background*  
*Part 2: Application*  
**Part 3: Questions**

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**One** 17

Is uncertainty of performance aspects a useful statistic to support conceptual design?

1. Very important
2. Important
3. Less important
4. Unimportant

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**Two** 18

Has uncertainty propagation and sensitivity analysis the potential to add value to the design process by generating extra design information?

1. Strongly agree
2. Somewhat agree
3. Somewhat disagree
4. Strongly disagree

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**Three** 19

Would you benefit from applying uncertainty propagation and sensitivity analysis to your current projects?

1. Strongly agree
2. Somewhat agree
3. Somewhat disagree
4. Strongly disagree


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Four 20

How do you assess the potential of the prototype to reduce time turning over simulation projects?

1. Very high
2. High
3. Medium
4. Low
5. Very low


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Five 21

How do you assess the potential reducing design iterations using uncertainty propagation and sensitivity analysis?

1. Very high
2. High
3. Medium
4. Low
5. Very low


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Six 22

Is the UP/SA analysis workflow transparent enough to be able to communicate its advantages and disadvantages to the design team?

1. Strongly agree
2. Somewhat agree
3. Somewhat disagree
4. Strongly disagree

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Seven 23

How does the risk assessment of the economic performance of design alternatives (e.g. based on energy demand predictions) fit your service portfolio?

1. Very good
2. Good
3. Not really
4. It does not


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Eight 24

How does the risk assessment of technical design decisions (e.g. on comfort) fit your service portfolio?

1. Very good
2. Good
3. Not really
4. It does not


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Nine 25

Which project stakeholder will benefit most from employing BPS with uncertainty propagation and sensitivity analysis?

1. Client
2. Occupant
3. Design team
4. Climate engineer
5. Others

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Ten 26

Do you assess extra computational support useful to support selecting the most appropriate design alternative?

1. Very important
2. Important
3. Less important
4. Unimportant

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Eleven 27

Are numeric optimization techniques useful to be applied during conceptual design?

1. Strongly agree
2. Somewhat agree
3. Somewhat disagree
4. Strongly disagree

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**Thank you!**

*Part 1: Background*  
*Part 2: Application*  
*Part 3: Questions*

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## **Curriculum vitae**

Christian Struck was born on 28 February 1973 in Berlin, Germany. He graduated in 2000 as Dipl.-Ing. (FH) in Building Services from the University of Applied Sciences Berlin in Germany, today Beuth Hochschule. He graduated on the subject of "Building conditioning concepts making use of the thermally activated building mass". Thereafter, he worked as consulting engineer at Buro Happold in Leeds, Great Britain in their Computational Simulation and Analysis group. In April 2005 he started his PhD research in the Building Physics and Services group at the Department of the Built Environment, Eindhoven University of Technology, the Netherlands of which the results are presented in this dissertation. Since 2009 he is employed as a senior scientist at the Lucerne University of Applied Sciences and Arts in Switzerland. He has published one book chapter and more than 35 articles in international journals, conferences and professional magazines. Furthermore, he won the Quality of Life contest 2010 by the Dalle Molle Foundation.