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An Exploration of the Option Space in Student Design Projects for Uncertainty and Sensitivity Analysis with Performance Simulation

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Abstract. *This paper describes research conducted to gather empirical evidence on extent, character and content of the option space in building design projects, from the perspective of a climate engineer using building performance simulation for concept evaluation. The goal is to support uncertainty analysis and sensitivity analysis integrated to building performance simulation (BPS) tools. The integration will need to assist design rather than automate design, allowing a spontaneous, creative and flexible process that acknowledges the expertise of the design team members. The paper investigates the emergent option space and its inherent uncertainties of an artificial setting (student design studios). The preliminary findings provide empirical evidence of the high variability of the option space that can be subjected to uncertainty analysis and sensitivity analysis.*

1 Introduction

Building performance simulation (BPS) allows studying the relationships between building design parameters (e.g. glazing percentage, thermal capacity) and the building's performance (e.g. peak and annual heating or cooling demands). In engineering, statistical techniques are used to study the propagation of uncertainties, and sensitivity of simulation results to perturbation of input parameters. The application of these techniques to the domain of building performance analysis has been successfully demonstrated by de Wit (2001) and Macdonald (2002) among others. Examples of parameters that were addressed in the past are, for instance, material properties (moisture content, conductivity) or design variables (building volume, thermal mass, and window to wall ratio).

Uncertainty and sensitivity analysis coupled with BPS has the potential to be used for accuracy- and design robustness assessment as well as design guidance. When uncertainty and sensitivity analysis are to be used to guide building design, knowledge about the option space to which the analysis is applied is important. While there are some general descriptions of this design process (for instance the RIBA Plan of Work), specific projects are highly individual, dynamic and iterative. They also often come with a project-dependent list of design aspects and parameters of interest. As a consequence, most research projects that aim to provide *general* computational guidance for building engineering – especially those aimed at the early stages of building design – fail to connect to actual analysis needs of the design team. Also, it appears that uncertainty and sensitivity analysis in the field is commonly dedicated to the solution space rather than the design option space.

This paper reports an initial effort to gather empirical evidence on actual emergence of design parameter to form concepts in building design projects, the related uncertainties, and the interest of design teams in specific subsets of these parameters. While there are some theories that are often quoted in the literature on the development of design tools, especially the assumption that the number of parameters and the accuracy of these parameters will increase asymptotically with progressing design, e.g., Torcellini and Ellis (2006), other bodies of knowledge point towards the iterative nature of the design process and suggest a more random development of this information, e.g., Eastman (1999, p 15). The findings of this work will inform the development of novel approaches that employ the use of uncertainty analysis and sensitivity analysis in building design. The challenge in such approaches lies in taking into account that these approaches will need to assist design rather than automate design, allowing a spontaneous, creative and flexible process that acknowledges the expertise of the participating design disciplines.

2 The design option space

The option space plays a role when a number of parameter and subsystem combinations exist that are equally likely to meet the posed performance requirements. It represents the pool of options as input to performance prediction and evaluation prior to selection. To evaluate the performance of parameter and subsystem combinations clear performance requirements are required.

There are a number of explicit constraints that limit the option space from the beginning of the building design process. At first there are the building regulations, which prescribe 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 set up and working of the design team. Those constraints to the option space are not further elaborated on in this paper.

Design decisions taken during conceptual design have a considerable impact on the final building performance. This is in spite of the fact that these design decisions are often based on incorrect, incomplete or highly complex information (Groot et al., 1999). That causes a risk of the building performance failing to meet the performance requirements. To quantify the risk of performance failure building performance simulation tools expanded with uncertainty analysis can be used. Uncertainty analysis enables the quantification of uncertainty in the simulated performance indicator due to uncertainty introduced by the simulation input data. Efforts are underway that tie techniques for uncertainty and sensitivity analysis to BPS-tools (Hopfe et al, 2007). The studies reported make use of prototypes to asses the value of the implementation to design practice.

Practitioners follow different approaches to design but have in common that they apply explicit and/or implicit design experience to projects. When considering a building design as a multidisciplinary integrated system it can be described by subsystems, aspect–systems, and parameters. Whilst a subsystem is a subset of elements that contribute to a physical phenomenon, e.g., building structure, aspect–systems are a subset of relationships which collectively describe a particular performance aspect like, for instance, thermal comfort. (van Nederveen and Tolman, 2001; Ten Haaf et al. , 2002; Blanchard and Fabrycky, 1998).

For the use with BPS–tools, integrated building systems are represented using parameters. Whilst, design parameters, e.g., window to wall ratio, can be chosen between bounds, sub- and aspect systems are combinations of discrete parameters that describe its performance sufficiently. Primary parameters are characteristic for a systems integrated performance, e.g., thermal resistance of walls, whilst secondary parameters describe a systems specification, e.g., conductivity of the outer leaf of an external wall.

Architects and engineers use all three system descriptors subsystems, aspect–systems and parameters in design practice. To facilitate an uncertainty analysis it is important to associate uncertainties to the input data to building performance simulation tools. Currently, most tools are limited to parametric input, which makes uncertainty quantification of subsystem combinations a cost intensive task. Efforts are reported that reduce the parametric input to building performance simulation tools to the most crucial parameters, whilst assigning default values to others. Limiting the level of detail required for the model definition enables a quick analysis turnaround of fundamentally different system and parameter combinations but reduces the accuracy of the results and limits the use of the tool and model for more detailed analysis, e.g., Itard (2003) , and Urban and Glicksman (2006).

Efforts have been published by Clarke et al. (1991) that aim to map the option space associated to the thermal properties of building construction materials, and by Morbitzer (2003) that associate evaluated and fixed design parameter to particular (RIBA) design stages from an architectural perspective. However, little is known about the option space from which subsystems and aspect-systems are selected. The paper aims to provide some insight on that subject. As the field is very wide the scope was limited by choosing the perspective of the climate engineer with experience in the use of building performance simulations, and by considering new build commercial buildings only.

3 Methodology – Empirical research

There are several approaches for empirical research in design. The object of the study can consist of a real design process in practice, or it can be an artificial experiment. In general, the study of real-life design processes (e.g. Badke-Schaub and Frankenberger, 1999; Emmitt, 2001) requires an enormous effort to gather data, as design processes can take a long time and can be very complex. However, this does allow the research to study design taking place in situ, embedded in the organizational and social frameworks that provide its context (Pahl et al, 1999). Artificial design processes (e.g. Macmillan et al, 2000; Austin et al, 2001) normally have a more focused area of research. They allow the researcher to study only one aspect or part of the design process, and to compare different teams working on the same problem. However, artificial design processes lack the context that is encountered in real design processes. The study of a design project can take place directly or indirectly. In direct observation a non-participating person records the ongoing design process; in indirect observations the actors in the design process themselves provide information on that process by means of interviews, diary sheets or questionnaires.

The student design project studied in this research is an assignment given to undergraduate students, in their second year on the Environmental Building Program at the University of Plymouth in the UK. The students undertake the projects in multi-disciplinary design teams of three to four students, which study towards different degrees: Architectural Technology, Construction Management, Building Surveying and/or Environmental Surveying.

The students were asked to develop a design based on a predefined design brief. This setting allows studying different teams working within the same brief, and 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). It 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 and could be used to measure a point in time where uncertainties related to design parameters have been reduced to zero. Table 1, indicates the characteristics of the collected data.

Table 1. Overview of important characteristics of collected data

	Artificial design projects
1. Aim	Train integrated design in an educational environment
2. Method	Direct observations of student projects
3. Character	Transient process – Project specific; Integrated design; Educational environment

The design brief requires a new building for the Faculty of Technology at the current site of the Brunel Laboratories at the heart of the University of Plymouth Campus. The design is to provide laboratory facilities, 2 large and 4 small lecture theatres, high-quality offices, an administration section and underground car parking on a constrained inner-campus location, forcing a high-rise scheme. The project is to be a high-tech but sustainable flagship project for the University.

4 Results

The emergence and development of parameters within ten parallel design projects was observed by the lecturer during design surgeries, over a course of ten weeks. Observation was partly pre-structured and partly open: a checklist of relevant parameters as described in Table 1 was used, constructed from parameters occurring in BESTEST cases, the IAI-IFC structure, and in EnergyPlus input data files. This list (see table 2) was augmented with the notion of “non-predefined parameters”, to be noted during the surgeries and added as per occurrence.

Table 2. Parameters observed from student projects.

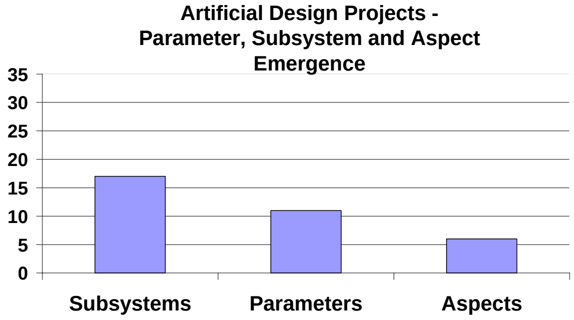
building position	wall material and thickness
orientation	roof material and thickness
access points	floor material and thickness

number of storey	
load-bearing structure	color scheme
thermal mass	finishes
floor size	heating/cooling plant
room size	end-equipment in rooms
internal access routes	artificial lighting
	day lighting
type of facade	occupancy scheme, internal gains
façade materials	air change rate
infiltration and air tightness	
	HVAC system parameters
wall-window relation	size of plant room
window and door position	location of plant room
U-value, g-value, light transmission	
	(plus “non-predefined parameters” introduced by design team)

Results for one of the design projects (selected arbitrary) are presented in Appendix 1. The results show which parameters, sub-systems and which aspect-systems were considered in consecutive weeks. The collected data was analyzed to establish the extent to which students use parameters, subsystems or aspects for building design. Furthermore, the number of parameters considered during the progressing design was mapped across the groups.

The data collected from different teams comes in non-uniform formats. To analyze the data it has to be brought into a common format. The process of formalization poses a source for errors if the context in which the data was presented cannot be captured. An example of data formatting is given for the formalized parameter, functional zoning. Bearing in mind the context, the original data presented as, arrangements of space and function, functional zoning and topology were grouped together and referred to as one item, functional zoning for further analysis.

Figure 1, shows the number of items identified for each category. After ten weeks of work the example student design team identified 17 subsystems, 13 parameters and 7 aspect-systems. It can be noticed that the number of subsystems is significantly larger than the number of parameter and aspects identified. The items being identified for each category were given scores (reported in brackets) for each occasion they were reported. The items with the highest scores were assessed being of particular concern to the design team. The highest scores were achieved for the subsystems – façade (3) and structure (4), the parameter – glass percentage (3) and functional zoning, (4) and the aspect energy use (3).



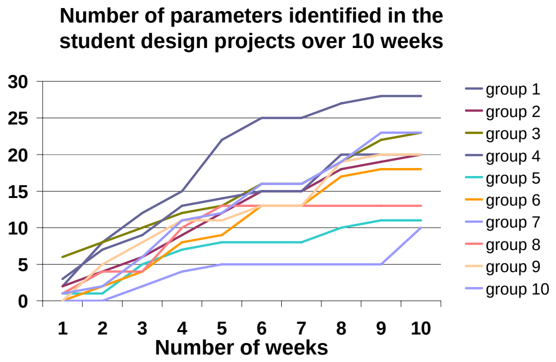


Fig 1. Artificial design projects – Number of identified parameter, subsystems and aspects for one student design team

Fig 2. Real-life design projects – Number of identified parameter, subsystems and aspects

The parameter emergence for the full group of student projects is presented in figure 2. This graph only represents the number of parameters identified, not the full accuracy with which these parameters are set. Also, the same number might represent different parameters. Note the difference in parameters emerged after 10 weeks, which differs by a factor 2.8 between group 1 and group 7. It is noted that this difference is not necessarily an indication of the one group being better than the other; some groups work more on the architectural concept for a longer time, while others are faster in going for technology decisions and parameters in the list observed.

5 Future use of building performance simulation with uncertainty and sensitivity analysis

If a design problem is complex, BPS-tools are a useful measure to evaluate concept performance with regards to performance requirements as energy and comfort. Usually there are a number of options evaluated that are equally likely to meet a set amount of performance requirements. The number of potential design options depends on the extent of the option space. Based on the previous section one can conclude that the option space from which designers derive their design concepts is extensive.

The use of detailed BPS – tools requires the definition of integrated concepts and its subsystems parametrically. The amount of parameters required for the concept definition is great. As an example, the Energy Plus office building – example model file “MultiStory.idf” provided freely with the software installation is composed of approx. 2500 parameters. Replacing subsystems with subsystem-alternatives comes at not insignificant costs. Efforts are reported that aim at reducing the effort required for evaluating different design options during the early design stages by limiting the tools parameter input mask to primary parameter only (Itard, 2003, Urban and Glicksman, 2006). The number of parameters required by the tools described in these references is approx. 25 only.

Based on the presented data one can conceptually visualize the decrease of the performance uncertainty over the duration of the student projects (see figure 3). Figure 3 shows the uncertainty remaining within the student design projects is still approx. 25%. It also indicates that the concept development is not completed yet from the perspective of the climate engineer by using the base line of 25 primary parameters.
Figure 4 shows how results from uncertainty and sensitivity analysis are expected to provide design information when used early in the process. Ideally, it allows screening the option space for parameter, subsystems and aspect-systems on their impact on the chosen performance indicator. In this context it is very important to know about the extent and the content of the available option space.

There are different approaches available for uncertainty and sensitivity analysis. One approach, global approach, provides a measure for the *total* uncertainty of a performance indicator by perturbing all model input parameters simultaneously. An indication of the strength and direction impact of contributing parameters on the total uncertainty and be derived from a subsequent regression analysis. Another approach, local approach, is based on the perturbation of individual parameters and provides a measure for the uncertainty on one performance indicator, due to the impact of the individual parameter. The calculated *individual* uncertainties can be used as sensitivity measure. Results from those two approaches applied to a one zone building model (Bestest Case 600) are presented in figure 4. Six parameters were considered during the analysis ranging from window to wall ratio to the insulation standard represented by the wall thermal resistance.

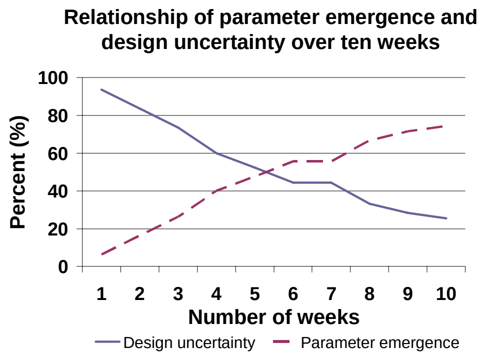


Fig 3. Emergence of primary design parameter up to the sixth week of the student project and decline of design uncertainty [1].

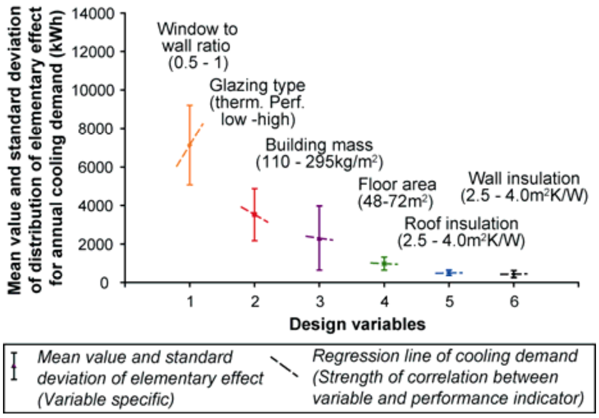


Fig 4. Design variables - Proposed combined presentation of individual and total sensitivities for annual cooling demand (Struck and Hensen, 2007)

[1] Parameter emergence: Emerged design parameters (cumulative mean value across 10 design teams) per week; Design uncertainty: Mean value of emerged parameters related to 25 parameters as from literature.

6 Conclusions

The authors argue that BPS–tools have the potential to provide design guidance during the conceptual phases when expanded with techniques for uncertainty and sensitivity analysis. Whilst the option space is a great resource for creative designs it also presents a substantial source of uncertainty. This paper explores the option space from student design projects. The aim was to investigate its extent and character to inform future efforts to improve the use of building performance simulation for concept evaluation. The perspective chosen was from a climate engineer using building simulations tool for design performance analysis.

The option space exposed from the research initiative contains items as parameter, subsystems and aspect-systems. Across the three items the option space was found to be extensive with 17 subsystems, 13 parameters and 7 aspects–systems. Corresponding with work by Austin et al (2001) it was found that novice designers (students) seem preferring to work with subsystems, which represent existing design solution, rather than more abstract parameter-based or aspect-based approaches.

Having established an approx. number of 25 primary design parameters it was concluded that the design uncertainty still inherent in the student design projects is 25% in week ten.

It is expected that building performance simulation tools when expanded with uncertainty and sensitivity analysis have the potential to provide design guidance during conceptual design. However, state of the art tools are dominated by parametric data input. The definition of a multi zone model of a commercial building generated in Energy Plus can easily exceed 2500 parameter. The evaluation of different subsystem combinations can therefore become a cost intensive task.

8 References

Austin, P., Steele J., Macmillan S., Kirby P. and Spence R. (2001). “Mapping the Conceptual Design Activity of Interdisciplinary Teams”. Design Studies Vol. 22 No.3, pp. 211-223.

Badke-Schaub P. and Frankenberger E. (1999). “Analysis of Design Projects”. Design Studies, Vol. 20 No.5, pp. 465-480.

Ball, L.J., Ormerod, T.C. and Morley, N.J. (2004) “Spontaneous analogising in engineering design: a comparative analysis of experts and novices”. Design Studies Vol. 25**,** pp. 495–508.

Blanchard, B. S. and W. J. Fabrycky (1998). System engineering and analysis. Upper Saddle River, NJ: Prentice Hall.

Brand, S. (1995) How Buildings Learn - What Happens After They’re Built. New York, NY: Penguin.

Clarke, J. A., P. P. Yaneske, et al. (1991). The harmonisation of thermal properties of building materials. Garston, Watford, UK: BRE.

Eastman, C., 1999. Building product models: computer environments supporting design and construction. Baton Roca, FL: CRC Press

Emmitt S. (2001). “Observing the act of specification”. Design Studies Vol. 22 No.5, pp. 397-408.

Groot, E. H. d., S. M. Mallory-Hill, et al. (1999). “A Decision Support System for Preliminary Design”. Durability of Building Materials and Components Conference, Vancouver, Canada, NRC Research Press.

ten Haaf, W., H. Bikker, et al. (2002). Fundamentals of Business Engineering and Management. Delft, The Netherlands: Delft University Press.

Hopfe, C. J., C. Struck, et al. (2007). “Uncertainty Analysis For Building Performance Simulation – A Comparison Of Four Tools”. 10th Int. IBPSA Conference, Tshingua University Beijing/China,, International Building Performance Simulation Association.

Itard, L. (2003) “H.e.n.k., A Software Tool For The Integrated Design Of Buildings And Installations In The Early Design Stage”. Eighth International IBPSA Conference. Eindhoven, Netherlands.

van Nederveen, S. and F. Tolman (2001). "Neutral object tree support for inter-discipline communication in large-scale construction." ITcon - Journal of Information Technology in Construction 6: 35-44.

Pahl G., Badke-Schaub P. and Frankenberger E. (1999). “Résumé of 12 years interdisciplinary empirical studies of engineering design in Germany”. Design Studies Vol. 20 No.5, pp.481-494.

Macdonald, I, (2002). Quantifying the effects of uncertainty in building simulation. Thesis (PhD). Glasgow: University of Strathclyde

Macmillan S., Steele J., Kirby P., Spence R. and Austin, S. (2000). “Mapping the design process during the conceptual phase of building projects”. Proc of CIB W96 Conference, Design Management in the Architectural and Engineering Design Office, Atlanta, USA, pp. 97-107.

Morbitzer, C. (2003) Towards The Integration Of Simulation Into The Building Design Process. Department Of Mechanical Engineering, Energy System Research Unit. Glasgow, University Of Strathclyde.

Struck, C. and Hensen, J. (2007) “On Supporting Design Decisions in Conceptual Design Addressing Specification Uncertainties Using Performance Simulation”. 10th Int. IBPSA Conference. Tshingua University Beijing/China, International Building Performance Simulation Association.

Torcellini, P. and P. Ellis (2006) “Early phase design methods”. Project presentation, Washington DC, USA, National Renewable Energy Laboratory

Urban, B. and Glicksman, L. (2006) “The MIT Design Advisor - a fast, simple tool for energy efficient building design”. SimBuild 2006. Massachusetts Institute of Technology, Cambridge, MA, USA.

de Wit, S., (2001). Uncertainty in predictions of thermal comfort in buildings. Thesis (PhD). Delft: Delft University of Technology

Appendix 1 - Parameter emergence and consideration of subsystems and aspect systems for a student project

Week:	Parameters:	Subsystems:	Aspect systems:
1	o Building volume (crude) o Site lay-out + Urban context	o Structure (high-rise) o Volumes (general lay-out) o Topology (Architectural lay-out/ internal organization) o services available on site	o Energy use (passive solar heating) o Architecture (organization)
2	o Building massing (4 to 5 storey) o Glazing percentage (high for labs)	o Function (Rooftop restaurant) o Green roof (sedum) o Structure (steel or timber frame)	o None
3	o Orientation o Building massing (8 storeys) o Glazing percentage (window-wall ratio 50%)	o Structure (pre-cast concrete frame with gluelam roof beam) o Day lighting (solar chimney/ atrium) o Facade (aluminum system)	o Air flow/ comfort (natural ventilation)
4	o Façade specification (scale 1:5) - material layers - thickness, area - airthightness	o Façade (aluminum veil façade for parking garage) o Hempcrete wall towards library	o Air flow (infiltration, ventilation)
5	o Size plant rooms (3 plant rooms) o Glazed atrium floor o Layout, rough position of walls, windows, doors	o Building services (air source heat pumps) o Façade (curtain wall)	o Day lighting o Comfort heating and cooling
6	o room size o floor size o thermal mass Start with bill of quantities	o Ventilation: cross ventilation	start with construction process Gantt chart
7	No design progress	Team focusing on construction site management issues	
8	o Building raised for parking garage		o Natural ventilation in parking
9	o Pipe sizes, routing	o Full services lay-out	
10	No design progress	Team focusing on presentation	