An investigation of the option space in conceptual building design for advanced building simulation

Struck, C., Wilde, P.J.C.J. de, Hopfe, C.J. & Hensen, J.L.M. (2009).
An investigation of the option space in conceptual building design for advanced building simulation.
Advanced Engineering Informatics, 23, 386-395.

An Investigation of the Option Space in Conceptual Building Design for Advanced Building Simulation

Christian Struck[1,*], Pieter J.C.J. de Wilde[2], Christina J. Hopfe[1] and Jan L. M. Hensen[1]

[1] Eindhoven University of Technology, Den Dolech 2, P.O.Box 513, 5600MB Eindhoven, The Netherlands; [2] University of Plymouth, Drake Circus PL4 8AA, Plymouth, United Kingdom

Abstract

This article describes research conducted to gather empirical evidence on size, character and content of the option space in building design projects. This option space is the key starting point for the work of any climate engineer using building performance simulation who is supporting the design process. The underlying goal is to strengthen the role of advanced computing in building design, especially in the early conceptual stage, through a better integration of building performance simulation tools augmented with uncertainty analysis and sensitivity analysis. Better 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. This research investigates and contrasts emergent option spaces and their inherent uncertainties in an artificial setting (student design studios) and in real-life scenarios (commercial design project case studies). The findings provide empirical evidence of the high variability of the option space that can be subjected to uncertainty analysis and sensitivity analysis.

[*] Author to whom correspondence should be addressed.
E-mail: C.Struck@tue.nl; Tel.: 0031 (0)40 247 5790; Fax.: 0031 (0)40 243 8595

Keywords (max.6)

Option space; conceptual building design; uncertainty analysis; sensitivity analysis; design concept evaluation, building performance simulation.

1 Introduction

Building performance simulation (BPS) allows studying the relationships between building design attributes (e.g. glazing percentage, thermal capacity etc.) and the building's performance (e.g. peak and annual heating or cooling demands etc.). In engineering, statistical techniques are used to study the propagation of uncertainties, and sensitivity of computational results to perturbation of simulation input parameters. The application of these techniques to the domain of building performance analysis has been successfully demonstrated by de Wit in [1] and Macdonald in [2]. Examples of attributes that were addressed in the past are for instance material properties like moisture content, conductivity; or design variables like building volume, thermal mass, window to wall ratio and insulation standard.

Uncertainty and sensitivity analysis coupled with BPS has the potential to be used for accuracy assessment, design robustness assessment, and design guidance. When uncertainty and sensitivity analysis are to be used to guide building design, the definition of the option space to which the analysis is applied becomes a crucial factor.

While there are some general descriptions of the building 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 attributes 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 article describes research conducted to gather empirical evidence on actual emergence of design attributes defining the concepts in building design projects, the related uncertainties, and the interest of design teams in specific subsets of these attributes. 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 attributes and the accuracy of these attributes will increase asymptotically with progressing design [3], 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 in [4]. 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.

The article is organized as follows. The first section provides an overview of the state–of–the-art in building design process and performance modeling research focusing on the characteristics of the conceptual design stage. The second section introduces the design option space and its representations, making use of systems theory. The third section introduces the research methodology employed to collect and analyze the data to map the design option space, followed by an introduction to the data sources used. The fourth section discusses the data obtained. The final sections five and six relate the outcomes to the requirements for a better integration of building performance analysis tools into the building design process, and give outlines for future research.

2 Design process perspectives

There is a substantial body of knowledge that deals with the design process, both in construction and more generally in the engineering disciplines. Seminal works in this field have been written by Simon [5], Lawson [6], Cross [7], and Roozenburg and Eekels [8]. Different models have been developed that describe 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* [9]. Recent contributions continue to expand this knowledge base by delving for instance into human factors, participatory design, user-centered design and human centered design [10] or the development of information systems that support project design [11], [12].

Within this frame, this article focuses on the emergence of building design information during the building design process. This information can then be used to generate further information about the performance of the design, and to guide further steps in the design process.

Koskela et al. [13] discern three perspectives to view design: transformation, flow and value generation, abbreviated TFV - conceptualization of design. 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 representing the conventional phased approaches as in for instance the RIBA design stages. 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. [14], [15] applying set based design to the construction industry. Pektas et al. [16] use the information flow perspective in design to manage iterative information cycles for process management. The value generation perspective is concerned with minimizing the loss of value during the process relative to the maximal value that can be achieved. Earlier efforts that relate to value generation and provision in construction where published by Rutten [17]. Rutten connects the value domain via functions to the design domain. The TFV conceptualization is particularly interesting as it enables a categorization and comparison of different process models.

2.1 Conceptual design

The focus during conceptual design is on the synthesis of integrated design representations. The early design stages are characterized by the need to evaluate a large number of design representations of different abstraction levels with little design information. Furthermore, there is typically a lack of knowledge about the interaction of design variables and sub-systems [18]. Engineering design problems are typically ill structured, which hinders the clear definition of the option space [19]. Per consequence not one but a number of design representations, also called concepts, are required to outline the option space.

In design practice that problem is tackled with case based reasoning [20]. Designers re-use their experience collected on earlier design projects. The quality of the resulting design solution is thereby directly influenced by the extent of professional experience. Stouffs [19] states that the developed design representations are both means and products. Means, as the design problem shifts and evolves during the definition process and products as they represent solutions to the earlier stated design problems.

2.2 Systems engineering

Efforts have been reported that relate building design to systems engineering [21], [22]. Systems engineering represents a formal description which was derived from processes found in other engineering disciplines such as aircraft design, etc. By applying systems theory, an integrated building system can be decomposed - using a top down approach - into elements as components, attributes and relationships. The components represent the operating parts of the systems and are characterized by attributes and relationships [23]. Blanchard et al. define the purpose of the preliminary design stage† to demonstrate that developed integrated system concepts maintain the performance requirements among others. Therefore complex systems require the application of engineering analysis tools which make use of engineering domain specific models.

2.3 Building performance simulation tools

To facilitate its use the tool has to fit the character of the design stage and the needs of the involved engineering disciplines. Clarke [24] recognized that the tool-box use of design tools need to evolve in computer supported building design environments. Augenbroe [25] associated his observations to two general approaches in analysis tool developments, the technology push and the technology pull approach. The technology pull approach is characterized being driven by demand as design questions, e.g. introducing simplified tools to design practice. The push approach embraces design oriented improvements of sophisticated tools. Both approaches lack multidisciplinary research efforts and fail to connect to the designer's viewpoint. Mora [20] gives a good overview of requirements to support conceptual structural design from architectural models which also

† Conceptual and preliminary design are synonyms originating from building and system engineering, respectively.

apply here. The most important development requirements relating to the conceptual design stage are:

- Assisting rather than automating design,
- Facilitate the quick generation of integrated solutions,
- Shorten synthesis analysis evaluation cycles,
- Support exploring the option space for selection of most suitable design alternatives.

Design decisions taken during conceptual design have a disproportional impact on the final building performance. That is because these decisions are often based on incorrect, incomplete or highly complex information [26]. This in turn causes a risk of the ultimate 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 potential deviations in the predicted performance due to uncertainty introduced by the simulation input data. Efforts are under ways that tie techniques for uncertainty and sensitivity analysis to BPS-tools [27], [28]. The studies reported make use of prototypes to evaluate the value of the implementation to design practice. However, to support exploring the option space information about its content and extent is essential as it serves as input to an uncertainty and sensitivity analysis.

2.4 The option space

The option space plays a role when a large number of attribute and subsystem combinations exist that are equally likely to meet the posed performance requirements. It represents the pool of alternatives that represent input to performance prediction, and which need evaluation prior the selection of a top-raking option. To evaluate the performance of attribute and subsystem combinations, measurable and predictable performance requirements are needed.

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. The above constraints to the option space are not further elaborated on in this article.

Practitioners have different approaches to design but have in common that they apply explicit or implicit design experience to projects. When considering a building design as a multidisciplinary integrated system it can be described using components, attributes and relationships, following the systems theory [23]. Components consist of input, process and output and may assume a variety of values to describe the system state. Attributes are the properties of the component and characterize the system. Relationships represent the link between the component and the attributes. The authors use a window to illustrate the system elements. A window and its frame can be considered a component. It has an impact on the relationship between building and environment by ,e.g., the energy required to compensate the heat loss in winter. Window attributes which determine the intensity of the relationship are for example glazing and frame heat transfer coefficients (u-values).

Architects and engineers use all three system elements, components, attributes and relationships in design practice. To facilitate an uncertainty analysis it is important to be able to associate uncertainties to the input data for building performance simulation models. 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 attributes, whilst assigning default values to others. Limiting the level of detail required for the model definition enables a quick analysis turnaround of fundamentally different subsystem and attribute combinations but reduces the accuracy of the results and limits the use of the tool and model for a more detailed analysis, e.g. [29]; [30].

Efforts have been published by Clarke [31] that aim to map the specific option space associated with the thermal properties of building construction materials, and by Morbitzer [32] that associates evaluated and fixed design attributes to particular RIBA design stages from an architectural perspective.

However little is known about the option space from which the systems elements are selected. This article aims to provide some insight on that subject. As the field is very wide the scope was limited by choosing the perspective of an environmental engineer with experience in the use of building performance simulation tools, and by considering new build commercial buildings only.

3 Methodology – Empirical research

The data considered for analysis originates from three different sources: student design projects, a review of realized design projects, and interviews with practitioners. This three-pronged approach allows to interrelate findings, and thereby to overcome some of the problems that would be inherent in following one line of research only. Findings are compared and where possible interrelated. The results are then used to review the prospects of supporting uncertainty and sensitivity analysis to provide design guidance.

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. [33]; [34]) 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 [33]. Artificial design processes (e.g.[35]; [36]) 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.

3.1 Artificial (student) design project observations

Students were asked to develop a design based on a predefined design brief. They were required to form multi-disciplinary design teams. The participating students were studying towards degrees in architectural technology, construction management, building- and environmental construction surveying.

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). 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 attributes have been reduced to zero.

The specific brief for the students asks them to design a large, multi-functional facility for the Faculty of Technology at the University of Plymouth, on a constrained location on the University campus which borders different buildings on all sides. 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 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 that takes on the role of flagship building of the University.

3.2 Real-life design project review

The material of three previously reported case studies is revisited and data extracted that contributes to the work on the option space [37]. The case studies focus on real-life projects from actual design practice that have been constructed in the Netherlands. In this case, 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 the review of design documentation as i.e. 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.

3.3 Interviews with practitioners

In 2005, 12 unstructured interviews with international building design professionals were performed and analyzed [38]. 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 the current computational support. The interviewees are active in different engineering disciplines that include climate and civil engineering, building physics, and architecture [39].

Table 1 indicates the characteristics of the collected data. All three research activities have in common that they target integrated building designs during the early design stages. The number of design disciplines participating was the largest for the student projects and interviews with practitioners and the smallest of for the real-life case studies. One important difference 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 design completion. Differently, 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 solution approaches.

3.4 Data analysis

The data collected from different people and by different research initiatives naturally comes in non-uniform formats. To analyze the data it requires a common format. After formatting it was categorized as elements of a system such as, components, attribute or relationship. The process of formatting and categorization 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 attribute 'functional zoning'. Bearing in mind the original context, the extracted raw data points with the same meaning as 'arrangements of space and function', 'functional zoning' and 'topology' were grouped and described as data points relating to 'functional zoning' for establishing counts.

As an example for categorizing data, consider the observed data point 'steelframe 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 'frame of the main structure'. The comparative data analysis using counts is based on formatted and categorized data.

4 Results

In this section the results of the above described individual research activities are presented and discussed. As the field is very wide the scope was limited choosing a perspective focusing on a number of key points. Those key points are design guidance for early design stages, multidisciplinary design, enhanced use of BPS –tools and supporting the selection of energy saving building components.

4.1 Artificial Design Projects - Attribute Emergence and Option Space

The student design project studied in this research is an assignment given to undergraduate students. 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.

The emergence and development of system elements 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 points as described in table 2 was used, constructed from BESTEST [40] case character, the IAI-IFC structure, and in EnergyPlus input data files. This checklist (see table 2) was augmented with the notion of “non-predefined points”, to be noted during the surgeries and added as per occurrence.

Results for the design projects are presented in table 3. The results show which attributes, building components and which relationships were considered in consecutive weeks. For further visualization of the student progress and way of working, figures 1 and 2 represent the status of the design project in week 5, when the students were asked to give an interim presentation. Of these, figure 1 shows a presentation drawing created in Google Sketchup.

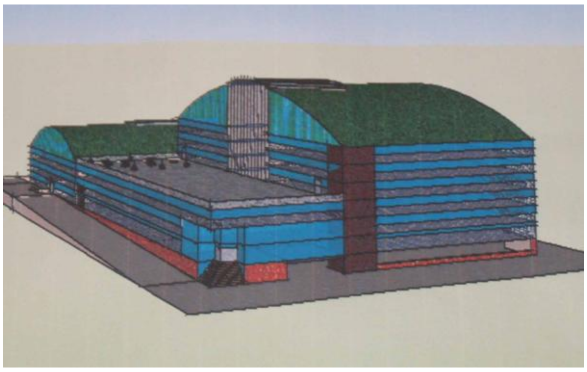

Figure **1** Building design presentation in week 5, drawn in Google Sketchup.

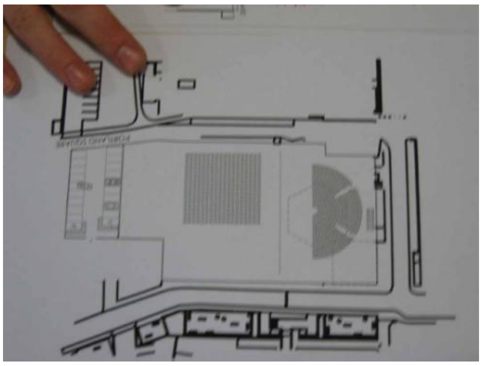

Figure 2 System configuration analysis for lecture theatres, showing two competing seating lay-outs (overlays on drawing)

Figure 2 shows a working drawing by the design team working on a parallel (different) project, which at this stage was investigating the lay-out for the lecture theatres. This represents a component (sub-system) based thinking, where a number of lecture theatre attributes that come with alternative configurations (theatre capacity, size, and geometry) are considered at once.

The collected data was analyzed to establish the extent to which students use attributes, components and relationships for building design. Another point of interest was whether system elements could be identified appearing repetitively, indication of importance, for comparison with results from the other two research initiatives. Furthermore, the number of system elements considered during the progressing design was mapped across the groups.

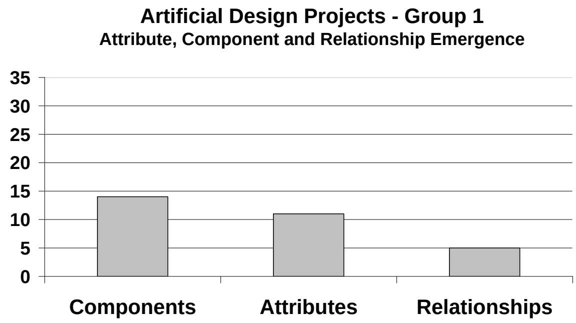

Figure 3 Artificial design projects – Number of identified attributes, components and relationships for one student design team, group 1.

Figure 3 shows the number of identified system elements for each category. After ten weeks of work the example student design team had identified 14 components, 11 attributes and 3 relationships. It can be noticed that the number of components is larger than the number of attributes and significant larger than the number of relationships identified.

The elements being identified for each category were given counts reported in brackets, for each occasion they were reported. The element with the highest count were assessed being of particular concern to the design team. The highest counts were achieved for the components building envelope (6) and building services (6), the glass attributes (3) and the relationship between the building and occupants represented by space ventilation and day lighting (3).

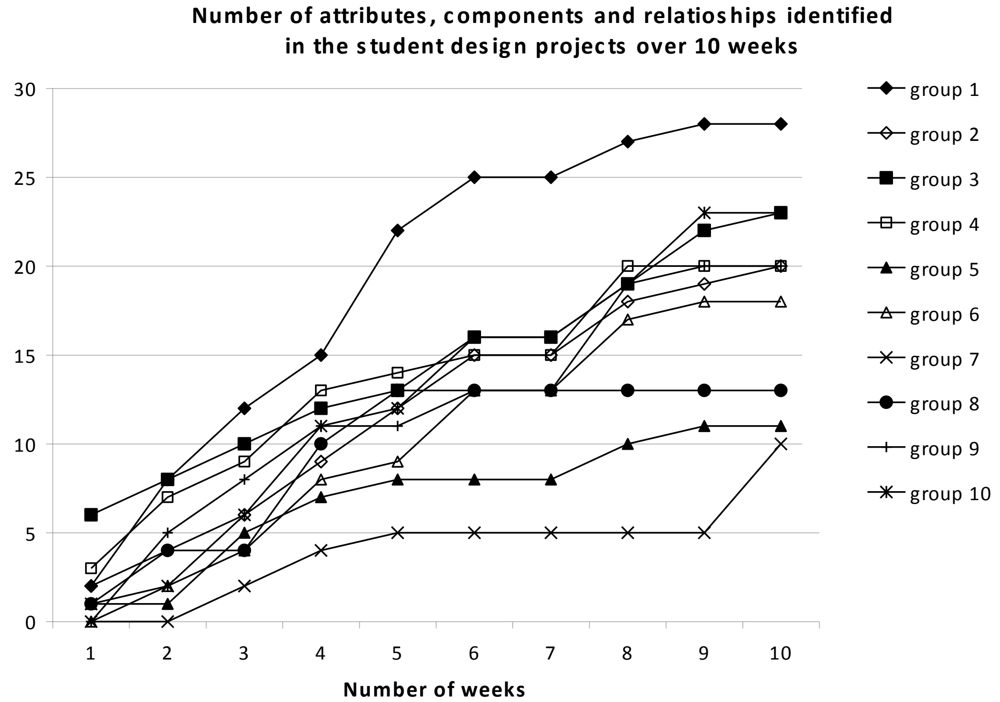

Figure 4 Artificial design projects – Number of identified attribute, components and relationships

The emergence of system elements for the full group of student projects is presented in figure 4. This graph only represents the number of elements identified, not the full accuracy with which these elements are set. Also, the same number might represent different elements. Note the difference in elements 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 elements in the list observed.

4.2 Real Life Projects - Option Space and Attribute Emergence in Design Practice

Three real building design cases from the Netherlands were considered for the analysis. All of them represent medium sized (~10.000m^2) office buildings. The buildings have in common that they are developed for the functional demand of an individual client. The buildings are the Rijnland Office, Leiden; ECN Building 42, Petten and the Dynamic office Kennemerplein, Haarlem. For more information on the cases see [41]. The main sources of information were the process maps for the early design stages [37]. The data was again grouped into three categories attribute, components, and relationships. Table 4 shows the grouped data from the cases.

Similarly as for the artificial design projects the extent of which the system elements are addressed was measured. Subsequently, the important elements within each of the three categories are identified.

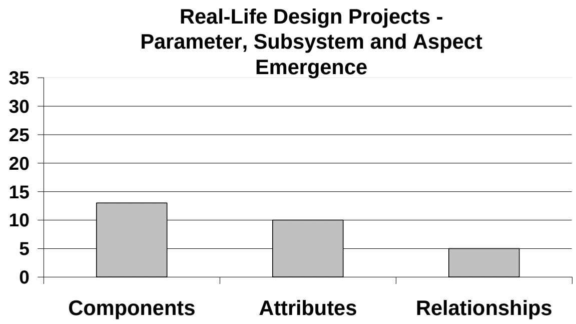

Figure 5 Real-life design projects – Number of identified attribute, components and relationships

Figure 5 shows the number of elements identified for each category. After the review of three case studies it can be noted that the number of components is larger than the number of attribute and relationships identified.

The elements identified for each category were given counts (reported in brackets) for each occasion they were reported. The elements with the highest counts were assessed being of particular importance to the practitioners. The highest count was achieved for the components cooling system (3) and atrium (3), the attribute functional zoning, (3) and the relationship between the building and the environment represented by building regulations (3) and energy performance (2). As the number of projects (samples) was three the highest count possible for an element to be ranked was also three.

4.3 Practitioner's Experience - Option Space and System Element Emergence in Design Practice

To gain a deeper understanding of the broadness of the option space in design practice, data was extracted from interviews with design practitioners. The 12 interviews were conducted in 2005 addressing the subject "Conceptual design and use of BPS for design guidance". The interviews were recorded which did allow revisiting the data for analysis.

In contrast to the work reported in section 4.1 and 4.2 these interviews did not concentrate on one specific building project but on the challenges experienced in the early design stages in general, across several projects. During the conversation example design problems and projects were discussed for illustrative purposes. Those design problems and example project form the data source. Table 5 shows the data extracted from interview 1 to 5.

The same method was used here as for the artificial and real–life design projects. Firstly the extent to which the system elements: attributes, components and relationships are addressed was established. Secondly, the importance of each of the three categories was established.

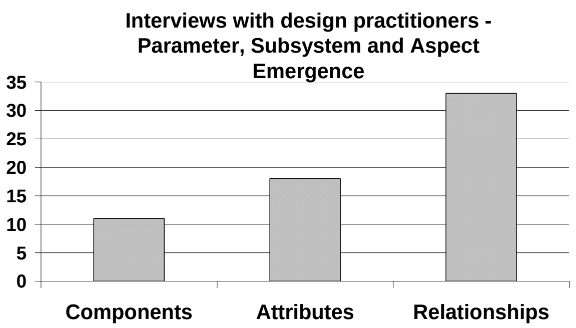

Figure 6 Interviews with 12 design practitioners – Number of identified attribute, components and relationships.

Figure 6 shows the number of elements identified for each category. After the review of 12 interviews with internationally practicing engineers it can be noticed that the number of relationships is significantly larger than the number of attribute and components identified.

The elements being identified for each category were given counts (reported in brackets) for each occasion they were reported. The element with the highest counts was assessed being of particular importance to the interviewees. The highest count was achieved for the component ventilation system (4) and window system (3), the attributes orientation (3), glazing properties (3), percentage glass (3) and the relationship between the building and occupants represented by thermal comfort (7) as well as the relationship between the building and environment indicated by energy use (6) and sustainability (5). Other high-scoring relationships were building – organization by flexibility (4) and building to owner investment costs (4).

5 Discussion

The extent of the option space can be estimated making use of the identified elements. From the data obtained a number of characteristics and categories could be derived (see table 6). Two characteristics are feasible for the representation of attributes, discrete and continuous. For the components four categories have been identified: architecture, building services, structure, and façade. Further, four types of relationships were identified; which relate to values as well being, economical- , functional- , and ecological value. Literature on the subject [42]; [17] suggest that there are more categories characterizing the option space in building design when deviating the attention from the collected data and targeted engineering domains. For instance Brand [42] identifies other component categories, also called “shearing layers”, as space plan, and interior. “Shearing layers” represent 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 practitioners make extensive use of relationships. The least considered element by the students is relationships, while the least considered element by practitioners is components. The weights of three elements from real-life projects follow the trend noticed from the student design projects, although they show slightly smaller numbers for all three elements.

It was expected that the data from real-life projects would follow the trend derived from interviews with practitioners. This expectation was not confirmed. There are a number of possible explanations for this observation:

- The real-life projects were reviewed rather than observed. The reviewing took place after design completion, which is naturally limited to the review of identified solutions to a well defined design problem. That 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, options, is significant.
- The size of the sample set. Three real-life projects were observed which might be too little to derive representative conclusions.
- The perspective of the review was limited to energy saving building components, which limits the considered relationships to building – environment indicated by energy demand.

Because of the identified limits the data does not give a complete overview of the attribute, components and relationships considered during design development. Therefore the data has been excluded for the qualitative analysis representation in figure 7. However, the data is significant for considering the extent of the option space. The preliminary option space derived from real-life design projects student design project and interviews with practitioners consists of a large number of attributes, four component categories and a large number of indicators for four different types of relationships.

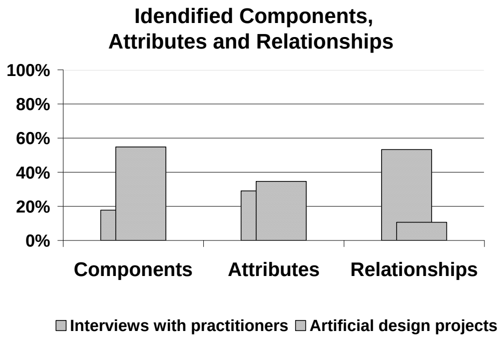

Figure 7 Comparison of attribute component and relationships of two research initiatives

The observed difference in how practitioners (expert designers) and students (novice designers) approach design corresponds to work published by Ball in [43]. Ball argues that expert designers work schema or relationship driven whilst novice designers work solution or case-driven. 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.

6 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 performances with regards to performance requirements as energy, comfort and day lighting. 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 work presented one can conclude that the option space from which design practitioners derive design concepts is extensive.

The use of detailed BPS – tools requires the parametric definition of integrated concepts and its components. The amount of attributes required for the concept definition is large. As an example, the Energy Plus office building – example model file “MultiStory.idf” which is provided freely with the software installation is composed of approx. 2500 attributes. Replacing subsystems with subsystem-alternatives comes at significant costs. Work has been published aiming at reducing the effort required for evaluating different design options during the early design stages by limiting the tools attribute input mask to primary attributes only. Such tools are for example h.e.n.k. and MIT Design Advisor [29], [30]. The number of input attributes required by the tools is approx. 25.

If one assumes the performance uncertainty of a concept to decrease linearly with the increase of design information, we can plot the performance uncertainty as in figure 8.

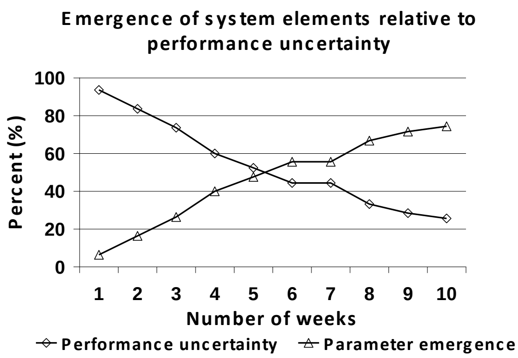

Figure 8 Emergence of system elements and decrease of performance uncertainty - Cumulative mean value across 10 design teams per week; Mean value of emerged elements related to 25 attributes.

The figure is based on the weekly cumulative mean value of the number of elements identified across all student groups. Due to the fact that mean values across the 10 student teams are visualized in figure 8, it still shows a performance uncertainty of approx. 26% after ten weeks. We also assume that the performance uncertainty is reduced to 0% once all 25 attributes are known serving as input to the simulation tool, which is a drastic simplification. Further to the uncertainty introduced by specifying the building concepts it is well known that uncertainties related to the simulation of the building performance are also introduced by:

- use and climate scenarios,
- choice of spatial discretisation and time steps,
- models of (complex) physical processes.

Therefore the authors propose the structured use of uncertainty and sensitivity analysis for:

- accuracy assessment of computational simulation results,
- performance robustness assessment of design concepts, and
- design guidance.

To provide design guidance, uncertainty and sensitivity analysis are ideally used for screening the option space for attributes, components and relationships that have a significant impact on one or multiple performance indicator. To facilitate the screening it is required to know about the extent and content of the option space. The technique to facilitate uncertainty and sensitivity analysis should allow assessing the interaction of system elements and be able to work with non-linear models. 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 attributes simultaneously. This is an indication of the strength and direction impact of contributing attributes on the total uncertainty and is derived from a regression analysis. Another approach, local sensitivity analysis, is based on the perturbation of individual attributes and provides a measure for the uncertainty on one performance indicator, due to the impact of the individual attribute. The calculated individual uncertainties can be used as sensitivity measure.

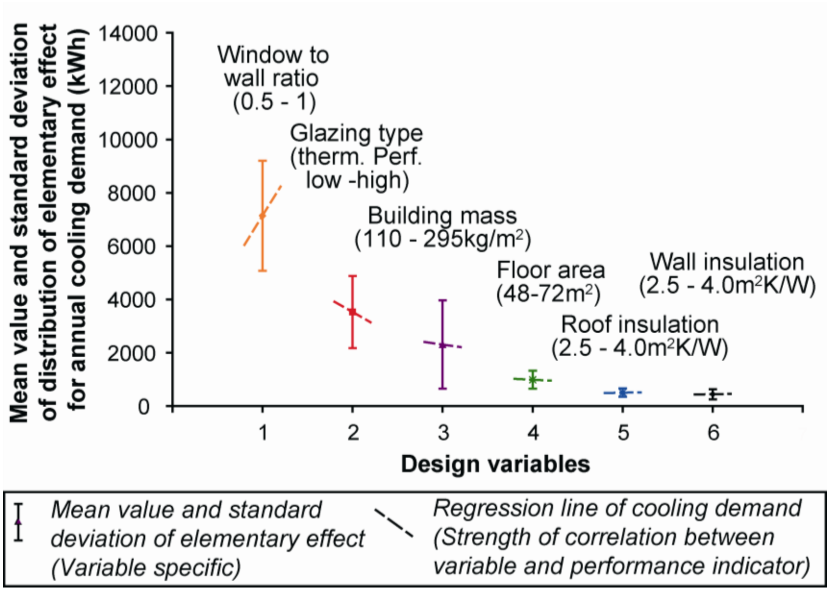

Figure 9 Design variables - Proposed combined presentation of individ-

ual and total sensitivities for annual cooling demand as in [44].

To indicate the potential of applying uncertainty and sensitivity analysis techniques for design guidance results of a case study are presented below. Figure 9 shows how results from uncertainty and sensitivity analysis are expected to provide design guidance when used early in the process. The case study was conducted to learn about the impact of six attributes on the annual cooling demand of a one zone building - Bestest Case 600. The six attributes considered and their range can be found in table 7.

The application of both techniques indicated the attributes window to wall ratio, glazing type and building mass to have significant impact on the performance metric annual cooling demand, whilst the impact of floor area and insulation standard of roof and wall are negligible. As depended on the building concept the impact of the attributes is expected to vary a structured procedure to isolate and attend to is required. By expanding BPS – tools with techniques for uncertainty and sensitivity analysis the option space can be searched methodically and decision taken based on impact of the system elements on the performance indicator of concern.

6 Conclusions

This article explores the design option space from three different research activities student design projects, real-life building projects and interviews with design practitioners. The aim was to investigate its extent and character to educate future efforts to enhance the use of computational concept performance evaluation during the early design stages. The perspective chosen was from a climate engineer using building simulation tools for design performance analysis.

The option space exposed from the three research initiatives contains items as attributes, components and relationships.

The data did show that practitioners (expert designers) and students (novice designers) make use of all three elements. Corresponding with work by others it was found that students seem preferring working with components which present design solution, whilst practitioners prefer working with relationships. Conversely to the expectation that the observation from the real-life case studies align with what was learned interviewing practitioners the data follow the trend by the student design teams.

Engineering analysis using BPS – tools has the potential to improve the design process by reducing the amount of time needed for design iterations. In order to facilitate a better implementation the tools should comply with the following requirements:

- Facilitate the quick generation of integrated solutions,
- Shorten synthesis analysis evaluation cycles,
- Support exploring the option space for selection of most suitable design alternatives.

The authors argue that a BPS - tool with the capability to perform an uncertainty and sensitivity analysis has the potential to support those requirements. The presented research indicates the limits within the tool needs to be capable of operating. It needs to support the top –down design de-composition to allow concept definition with little parametric detail, but it also needs to support local backtracking, bottom-up, to add detail in areas where uncertainty needs to be reduced.

The tool needs to be able to work with components, attributes and relationships whereby the consideration of the anticipated user group is crucial. Whilst experienced designers prefer relationships novice designers prefer components.

The use of parametric attributes for uncertainty and sensitive analysis is reported in literature. However in order to allow uncertainty and sensitive analysis to deal with both components and relationships, more work is needed. For example the representation of components can be achieved via a set of fixed attributes which are, to the authors' best knowledge, not yet readily available. The representation of relationships has to be achieved via the prediction of representative performance indicators.

Tool developments are reported that limit the amount of input data about a factor 100 compared, 25 attributes, to the detailed simulation tools to allow a quick turnaround of evaluations of different subsystem combinations. However, those developments are typically limited with regards to their modeling resolution level.

Whilst a start was made on character and extend of the option space the dynamics could only be mapped from the student projects. As there is a clear difference between students and experts designing the preliminary conclusions are not representative for practitioners. More work is needed to capture the inherent dynamics and to consider other design disciplines and their interactions.

Acknowledgements

The authors like to acknowledge the contribution of the participating student teams, interviewees and design practitioners involved in the process of collecting the data. Furthermore we want to express our gratitude to the reviewers for the valuable comments.

8 References

[1] M. S. d. Wit, "Uncertainty in predictions of thermal comfort in buildings," in *Civiele Techniek*, vol. Ph.D. - Thesis. Delft, The Netherlands: Technische Universiteit Delft, 2001, pp. 215.

[2] I. Macdonald, "Quantifying the effects of uncertainty in building simulation," in *Department of Mechanical Engineering, Energy Systems Research Unit*, vol. Ph.D. - Thesis. Glasgow, UK: University of Strathclyde, 2002, pp. 253.

[3] P. Torcellini and P. Ellis, "Early-Phase Design Methods," vol. 2006. Washington, DC: Center for Buildings and Thermal Systems at National Renewable Energy Laboratory (NREL), 2006.

[4] C. M. Eastman, *Building Product Models: Computer Environments Supporting Design And Construction* Boca Raton, Florida: CRC Press LLC, 1999.

[5] H. A. Simon, *The Sciences of the Artificial*. Cambridge, Massachusetts: MIT Press, 1969.

[6] B. Lawson, *How Designers Think*. London: Architectural Press, 1980.

[7] N. Cross, *Engineering Design Methods: Strategies for Product Design*. Winchester: John Wiley & Sons, 1994.

[8] N. F. M. Roozenburg and J. Eekels, *Product design : fundamentals and methods* Chichester John Wiley & Sons Inc 1995.

[9] R. Birmingham, G. Cleland, R. Driver, and D. Maffin, *Understanding engineering design: context, theory, and practice*. London: Prentice Hall, 1997.

[10] T. Keinonen, "Design Contribution Square," *Advanced Engineering Informatics*, vol. 23, pp. 142-148, 2009.

[11] T. Hartmann, M. Fischer, and J. Haymaker, "Implementing information systems with project teams using ethnographic-action research," *Advanced Engineering Informatics*, vol. 23, pp. 57-67, 2009.

[12] A. Moum, C. Koch, and T. I. Haugen, "What did you learn from practice today? Exploring experiences from a Danish R&D effort in digital construction," *Advanced Engineering Informatics*, vol. In Press, Corrected Proof, 2009.

[13] L. Koskela, P. Huovila, and J. Leinonen, "Design Management in Building Construction: From Theory to Practice," *Journal of Construction Research*, vol. 3, pp. 1-16, 2002.

[14] K. Parrish, J.-M. Wong, I. R. Tommelein, and B. Stojadinovic, "Exploration of Set-Based Design for Reinforced Concrete Structures," presented at 15th Annual Conference of the International Group for Lean Construction IGLS 15, East Lansing, MI, USA, 2007.

[15] K. Parrish, J.-M. Wong, I. D. Tommelein, and B. Stojadinovic, "Set-based Design: Case Study on Innovative Hospital Design," presented at 16th Annual Conference of the International Group for Lean Construction (IGLC 16), Manchester, UK, 2008.

[16] S. T. Pektas and M. Pultar, "Modelling detailed information flows in building design with the parameter based design structure matrix," *Design Studies*, vol. 27, pp. pp. 99 - 122, 2006.

[17] P. G. S. Rutten, H. M. G. J. Trum, and M. F. T. Bax, "On the strategic design of buildings," presented at 15th IAPS-Conference Shifting Balances - Changing Roles in Policy,Research and Design, Eindhoven, The Netherlands, 1998.

[18] P. C. Matthews, "A Bayesian support tool for morphological design," *Advanced Engineering Informatics*, vol. 22, pp. 236-253, 2008.

[19] R. Stouffs, "Constructing design representations using a sortal approach," *Advanced Engineering Informatics*, vol. 22, pp. 71-89, 2008.

[20] R. Mora, C. Bédard, and H. Rivard, "A geometric modelling framework for conceptual structural design from early digital architectural models," *Advanced Engineering Informatics*, vol. 22, pp. 254-270, 2008.

[21] E. Djunaedy, J. Hensen, H. C. J., S. C., M. Trcka, and A. Yahiaoui, "Notes on building performance simulation and the role of IBPSA (keynote presentation)," presented at 11th Brazilian Congress of Thermal Sciences and Engineering - ENCIT, Curitiba, Brazil, 2006.

[22] A. Yahiaoui, A. E. K. Sahraoui, J. L. M. Hensen, and P. J. Brouwer, "A systems engineering environment for integrated building design," presented at European Systems Engineering Conference (EuSEC), Edinburgh, UK, 2006.

[23] B. S. Blanchard and W. J. Fabrycky, *System engineering and analysis*, 4th ed. Upper Saddle River, New Jersey: Pearson Prentice Hall, 2006.

[24] J. A. Clarke, *Energy simulation in building design*, 2nd ed. Oxford, UK: Butterworth-Heinemann, 2001.

[25] G. Augenbroe, "Integrated building performance evaluation in the early design stages," *Building and Environment*, vol. 27, pp. 149-161, 1992.

[26] E. H. d. Groot, S. M. Mallory-Hill, R. H. M. v. Zutphen, and B. d. Vries, "A Decision Support System for Preliminary Design," presented at 8dbmc- Durability of Building Materials and Components 8 Conference, Vancouver, Canada, 1999.

[27] C. J. Hopfe, C. Struck, P. Kotek, J. v. Schijndel, W. Plokker, and J. Hensen, "Uncertainty Analysis For Building Performance Simulation – A Comparison Of Four Tools," presented at 10th Int. IBPSA Conference, Tshingua University Beijing/China,, 2007.

[28] P. Heiselberg, H. Brohus, A. Hesselholt, H. Rasmussen, E. Seinre, and S. Thomas, "Application of sensitivity analysis in design of sustainable buildings," *Renewable Energy*, vol. 34, pp. 2030-2036, 2009.

[29] L. Itard, "H.e.n.k., A Software Tool For The Integrated Design Of Buildings And Installations In The Early Design Stage," presented at Eighth International IBPSA Conference, Eindhoven, Netherlands, 2003.

[30] B. Urban and L. Glicksman, "The MIT Design Advisor - a fast, simple tool for energy efficient building design," presented at SimBuild 2006, Massachusetts Institute of Technology, Cambridge, MA, USA, 2006.

[31] J. A. Clarke, P. P. Yaneske, and A. A. Pinney, "The harmonisation of thermal properties of building materials," BRE, Garston, Watford, UK Report TN91/6, 1991.

[32] C. Morbitzer, "Towards the Integration of Simulation into the Building Design Process," in *Department of Mechanical Engineering, Energy System Research Unit*, vol. Ph.D. - Thesis. Glasgow: University of Strathclyde, 2003 pp. 278.

[33] G. Pahl, P. Badke-Schaub, and E. Frankenberger, "Resume of 12 years interdisciplinary empirical studies of engineering design in Germany," *Design Studies*, vol. 20, pp. 481-494, 1999.

[34] S. Emmitt, "Observing the act of specification," *Design Studies*, vol. 22, pp. 397-408, 2001.

[35] S. Macmillan, J. Steele, P. Kirby, R. Spence, and S. Austin, "Mapping the design process during the conceptual phase of building projects," presented at Design Management in the Architectural and Engineering Design Office, Atlanta, USA, 2000.

[36] S. Austin, J. Steele, S. Macmillan, P. Kirby, and R. Spence, "Mapping the conceptual design activity of interdisciplinary teams," *Design Studies*, vol. 22, pp. 211-232, 2001.

[37] P. d. Wilde, "Computational support for the selection of energy saving building components," vol. Ph.D. - Thesis: Delft University of Technology, 2004

[38] C. J. Hopfe, C. Struck, G. Ulukavak Harputlugil, and J. Hensen, "Computational tools for building services design - professional's practice and wishes," presented at 17th International Air-conditioning and Ventilation Conference Prague, 2006.

[39] C. J. Hopfe, C. Struck, G. Ulukavak Harputlugil, J. Hensen, and P. d. Wilde, "Exploration of using building performance simulation tools for conceptual building design," presented at IBPSA-NVL conference, Delft, The Netherlands, 2005.

[40] R. Judkoff and J. Neymark, "International energy agency building energy simulation test (BESTEST) and diagnostic method," National Renewable Energy Laboratory NREL/TP-472-6231, 1995.

[41] P. d. Wilde, "Gebruik van simulatie-tools bij de integratie van energiebesparende componenten in gebouwen in de huidige ontwerppraktijk," Energie research centre of the Netherlands (ECN), Petten ECN-C-01-060, June 2001 2001.

[42] S. Brand, *How Buildings Learn - What Happens After They're Built .* New York: Penguin, 1995.

[43] L. J. Ball, T. C. Ormerod, and N. J. Morley, "Spontaneous analogising in engineering design: a comparative analysis of experts and novices," *Design Studies*, vol. 25, pp. 495–508, 2004.

[44] C. Struck and J. Hensen, "On Supporting Design Decisions in Conceptual Design Addressing Specification Uncertainties Using Performance Simulation," presented at 10th Int. IBPSA Conference, Tshingua University Beijing/China, 2007.

Table 1. Overview of data characteristics

	Artificial design projects	**Real-life design projects**	**Practitioners view**
1. Aim	Training integrated design in an education environment	Obtaining insight to evaluation and selection process for energy	Understanding where practitioners use BPS; Identification of bene-

		saving components in design practice and use of computational tools for support.	fits and drawbacks.
2. Method	Observation of student projects.	Interviews with practitioners & Review of project design documentation	Interviews with practitioners
3. Character	**Transient** process – Project specific; Integrated design; Educational environment	**Real** early design setting Project specific; Review across multiple disciplines (architects, HVAC consultant, simulation specialist).	Review of **ideal** early design expectation and experience; Non-project specific; Discipline specific.

Table 2. System elements 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)

Table 3. Attribute emergence and consideration of components and relationships for one student project, for week 1 to 3 as example.

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 glue-lam roof beam) ○ Facade (aluminum system)	○ Building and occupants, (indicated by: air flow/ comfort and day lighting)

Table 4. Attribute emergence and consideration of components and relationships for one real-life project, as example.

	Attributes	Components	Relationships
1 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	○ Building and owner, (indicated by budget)
		○ Low temp heating system	
		○ High temp cooling system	
		○ Atrium	
		○ Climate façade	

Table 5. Attribute emergence and consideration of components and relationships from interviews with 3 design practitioners, as example.

Intervie-wee	Attributes	Components	Relationships
1	○ Location of building	○ Façade	○ Building and environment (indicated by considering exposure to noise, wind, sun)
	○ Massing of envelope ○ Orientation	○ Building services	
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 occu-pants(indicated by consi-dering internal air flow and daylight availability)
	○ Thermal capaci-ty of structure ○ Percentage glass ○ Shading coeffi-cient	○ Building services	

Table 6, Identified attribute characteristics, component categories, relationships and associated values.

Pos.	**Attribute characteristics**	**Component categories**	**Relationships**	associated values
1	Discrete (i.e. location)	Architecture (i.e. Functional zones)	Building - Owner	Economical (i.e. Investment costs)
2	Continuous (i.e. internal gains)	Building services (i.e. Cooling system)	Building - Environment	Ecological (i.e. Energy use)
3		Structure (i.e. Steel frame)	Building - Occupants	Well being (i.e. Comfort)
4		Façade (i.e. Climate facade)	Building - Time	Strategic (i.e. Flexibility)

Table 7, Case study – varied attributes and their range

Attribute name	Attribute range
Window to wall ratio	0.5 - 1
Thermal performance of glazing type	Low - High
Building mass	110 – 295kg/m^2
Floor area	48 – 72m^2
Roof insulation, thermal resistance	2.5 – 4.0 m^2K/W
Wall insulation, thermal resistance	2.5 – 4.0 m^2K/W