Automated Design Space Exploration for Improved Early-Stage Decision-Making

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Summary

This paper addresses today's challenges in creating a building design. It focuses on the criteria of sustainable design and how it can be integrated into the conceptual design stages of office and administrative buildings. The conceptual design stages are of extraordinarily high importance because they have a profound impact on the later costs and performance of the resulting building. A careful investigation of the different design options is accordingly required. As the combination of the diverse design options usually results in a very large design space which can hardly be explored manually, designers can obtain considerable assistance from computer tools that are able to perform an automated design space exploration (ADSE). If they are to be of use, however, such tools need to be intuitive, helping the designers in the decision-making process without impeding creativity. This paper contributes towards the development of such tools by investigating the boundary conditions in place. To illustrate the concept, the paper presents a prototypical software tool which assists building designers in the creation of load-bearing steel and steel composite structures for a roughly defined building layout.

Keywords: conceptual design; structural feedback; performance predictions

1. Introduction

Architectural design is a complex process, which cannot be described as a linear sequence of individual steps or the result of a mathematical equation, but must be understood as an iterative approach instead. There are a number of different influences and various stakeholders, such as technical guidelines, legal regulations or specifications issued by the clients that limit the potential design space. During the course of the design process the concept therefore evolves from a conceptual, three-dimensional idea into a result that combines all aspects, from stakeholders as well as guidelines and other constraints.

In the analysis of the guidelines, it is very important to adjust the influence they exert at each design stage in order to define the scope of the design space. This adjustment is necessary because, on the one hand, designers run the risk of limiting the design space too early in the process without taking alternative solutions into consideration. Alternative solutions are an important step where designers get to know the spectrum of three-dimensional variations and how the individual aspects influence each other. On the other hand, the definition of the benchmarks has to be precise enough to transfer the designed space to the next design step without departing from the main idea of the original concept. Thus, it is always of particular importance to repeatedly check the given applied constraints, such as financial constraints, input by the clients or technical standards, in the different alternative designs.

Even with their experience-based typological knowledge and individual creativity, designers have to struggle with increasingly complex, specific and, above all, technical aspects in the design process. Designers need to work together with specialist engineers in this regard. Ecological and economic issues in particular (for example LEED or DGNB certifications for office buildings) become more and more relevant.

However, these specialist engineers are often involved at a fairly late stage in the intricate design process. Wherever possible, designers and architects have to think ahead and consider their relevant aspects well in advance in order to recognize the consequences and dependences for the design. To assess ecological or economic issues accurately early on in the design process, years of experience on the part of the architect or an extremely high time investment are necessary to emulate the knowledge of specialist engineers adequately.

Contemplating the consequences of individual decisions at an early stage of the building design process is an important work step for architects designing the three-dimensional concept. Most of the constraints designs are not well defined at this point, because there is no clear description of the model in a designer’s mind before the final design has emerged [1]. However, some quick, automatically generated feedback on the initial conceptual ideas offers designers the chance to increase the number of validated conceptual designs and at the same time reduce the time effort. The feedback can be related to the main supporting structure and the associated information on material quantities, production costs, sustainability, etc. These results help designers early on in the design process to obtain further decision criteria for or against alternative solutions and to optimize solutions without the need for specialist engineering knowledge. The more different structural solutions can be created, the more the designer can explore the design space for optimal solutions.

Automated Design Space Exploration (ADSE) accordingly has the potential to act as a valuable tool to assist the designer in this situation. In order to generate more than one optimum solution, it is necessary to make use of an assessment that provides several well-performing solutions. This is of importance, because the optimal solution may not correspond to the stakeholders’ original design intentions. It is vital to provide a means of comparing these results and choosing the one that appeals most and matches the intended purpose of the design best.

To illustrate the ADSE approach, this paper presents an implementation of the methods available with a software tool that supports the traditional sketch-based line of thought employed by designers. This lifts the draughtsman’s approach from the drawing-board and physical models to computer-aided volumetric models generating early proposals for steel and steel composite supporting structures.

2. Sustainability and conceptual design

Sustainable building activity means “to build economically and ecologically optimised buildings whose social competence lies in their functionality and flexibility” [2].

Adapting buildings to changes in society and, consequently, customized working processes and changes in office structures, requires not only a durable, energy efficient structure (material, depth of the building, span width, quantity and positions of building cores, etc.) but above all the customization to flexible, three-dimensional structures, in order to achieve the desired sustainability. In the early stages of the design process it is therefore important to assess different floor plans and layouts in order to meet the changing demands made on the structure by prospective occupants, with a minimum of effort. To this end, the main input should be aimed at reducing the building to its primary structure / shell construction. To offer this maximum on flexibility in office buildings, in order to have an important aspect of the sustainability achieved, designers have to consider certain aspects and addictions on the construction grid. For example a wide, open spaced floor offer a big variety on possible office structures like single- , group- , combi-offices or a business club, but in the same time it has limitations in the construction height, dimensions of the main structure, etc.. So in consultation with the occupant the mass of flexibility and all its dependencies has to be defined already in the early design process.

In addition, it is also important to define useful, sustainable information for the above-named criteria to maintain a high level of flexibility for the conversion of the structure. It is therefore important for architects and designers to begin with an optimized solution for the aforementioned aspects of sustainability right from the start of the designing process, because subsequent changes are both time-consuming and costly.

In order to find a sustainable solution for a structure, it is imperative to fulfil the ecological, economic and social aims. Compliance with social criteria should meet the needs of various stakeholders (user, owner etc.). This includes such aspects as efficient workplaces as well as the functionality and design of the building. Professional scientists develop utilization scenarios that make it possible to incorporate the changing demands on an office building into the design process. Flexible grids will be developed with the aid of known and future models of offices, and these will, in turn, influence the requirements for the supporting structure.

Taking the economic and ecological aspects into account when choosing the building materials and type of construction is a matter of course nowadays and is not mentioned separately in this paper.

Building geometry and various functional areas bring different technical requirements to bear on the supporting structure. The requirement profiles for the bearing structure can be deduced from these criteria which include spans, live load, additional dead load, serviceability, fire protection, etc. As a result, it is possible to judge the suitability of relevant building systems and their variations. A wise, informed choice of systems, structural components and materials makes it possible to optimize the mass of the respective ceiling systems, which ultimately has a favourable influence on the outlay for vertical bearing elements and foundations.

The DGNB (German Sustainable Building Council) and BNB (Assessment System for Sustainability of Federation Buildings) have compiled criteria catalogues for assessing the ecological sustainability. The data of every single criterion is collected over the entire lifecycle of the building. This covers the planning phase, construction phase, operation phase as well as the credits and debits from the dismantling, recycling and disposal at the end of the lifecycle. Databases, such as Ökobau.dat (2011) and Environmental Product Declarations (EPD) provide environmental indicators for different building materials and products. However, usually only the production phase, the credits and debits relating to the end of the relevant life cycle are recorded. The other phases cannot be represented at this stage due to the lack of available data. The processes of construction management can be estimated.

In analogy to the ecological assessment, the entire lifecycle of the building is taken into account for the economic analysis. The aim is to demonstrate the economic benefits of different construction

types and under which conditions which construction is suitable. To draw this comparison, such aspects as earthworks or finishes and service work have been disregarded. The material, production, erection, maintenance and disposal costs are included by way of life cycle outlay. A resource-efficient design serves to reduce the manufacturing costs. In many cases, material savings can be achieved by increasing the material strength. For example, the moderate difference in price compared to normal strength steels can often be compensated for by appropriate material savings [3]. The low transport and erection weight as well as the lower weld volume in shop production have a positive effect on the construction time, so the costs for the provision of the construction site facilities are reduced and the building can be put into use sooner. Recurring dimensions of both construction components and connection constructions support the rapid construction progress. This, moreover, allows the supporting structure to be employed for alternative purposes following appropriate modifications.
Depending on the requirements of the stakeholders, the construction systems can be the best solution for specific grids on an ecological and economic level. In order to find an “optimal” or “sustainable” solution for the construction systems, it is necessary to factor in both the ecological and economic criteria.

3. Integration into an architectural design

The afore mentioned criteria show that the big issue in sustainable design is the fact that it is influenced by many different decisions made by the stakeholders. There are numerous strategies available to achieve a sustainable design (different materials, higher insulation versus better technical systems …). More than ever before, sustainable designing accordingly involves a complex design space with a large number of different options (design variables) and conflicting criteria.

Since not every constraint can be defined precisely from the very beginning, it is necessary to make assumptions for those that are missing. Therefore, the aim is to complement the existing knowledge for designing new buildings and to develop tools for sustainable planning in the shape of design references, component lists and an IT-Tool for practical use.

With the currently available tools, however, designers can only compare a small number of variants because it is difficult to draw up, analyse and compare all the different variants manually. However, the analysis of as many different solutions as possible is required in order to obtain the best possible insight into the influence exerted by different parameters. Experience from previous projects helps designers to select good configurations for comparison. However, building projects exhibit a high degree of individuality along with the accompanying risk of missing best-performing solutions.

To address this issue, we decided to develop a prototype to assist designers in their decision-making in the early design stages. The tool provides fast feedback on changes in terms of sustainability. This enables draughtsmen to conduct a design space exploration (DSE), where the design space is the set of all possible solutions for a given problem. Nevertheless, any automated DSE is only as good as the accuracy of the results of the model-based quality evaluations, and they rely on the accuracy of parameters that are used in the evaluation models [4]. Furthermore, designers tend to be averse to computer-based design optimization since this is their field of work. This is why the assisting tool is not actually aimed to create the optimum solution, but to suggest different variations of possible solutions to assist designers in their decisions.

4. Related work

Optimization approaches in research and their application in building design are either general studies for building types that do not take the specific situation of the individual design case into account along with its environment; or there exist specifically tailored solutions for individual instances of design projects.

For example, [5] have developed a multi-criteria evaluation model for the selection of sustainable materials. This can help designers in their choices, but it will not help them to find new solutions. All the evaluated alternatives have to be entered by the designer.

[6] have introduced a new method, the Design Scenarios, to streamline the requirements definition, alternative generation, analysis, and decision-making processes in the conceptual design phase. All criteria from the different stakeholders are used to create a parametric model containing all these requirements. But here the parametric model has to be created by an architect from the Design Scenarios manually and no optimisation algorithms are included.

There are, moreover, a great many tools on the market that help designers to evaluate their design in terms of performance: the tool developed by [7], for instance, the Design Performance Viewer, which helps designers to assess building models with respect to energy performance.

Although there are many computational tools for describing, editing, analysing and evaluating design projects, there is still a lack of consistency between the knowledge visualization of the given domain (architecture, construction, machine building) and its internal representation in a computer program. This is one of the reasons why the initial design phase, the so-called conceptual design, is the least supported one [8].

5. Prototypical implementation

The concept ADSE has been implemented in a software prototype. With this prototype, the designer can export the required values, such as geometric data and the added constraints related to his first basic sketches, to a structure generator. Following the generation stage, the well-performing solutions are displayed. The structure generator can be restarted once the architect has adopted the design according to the feedback of the tool.

5.1 Workflow

In the first step, rectangular shapes can be sketched to define the initial footprints of the building. Based on these initial 2D footprint sketches, the designer can create volumetric building blocks, which follow a set of rules integrated into the software from building typology knowledge (see Fig. 1). The blocks can be modified in an environment set up using SketchUp, in a manner very similar to the way tangible blocks are positioned on a printed 2D map.

While creating and modifying the volumetric architectural model, a parametric functional structural design model (FSDM) is generated simultaneously, which serves as input for the automatic structure generator.

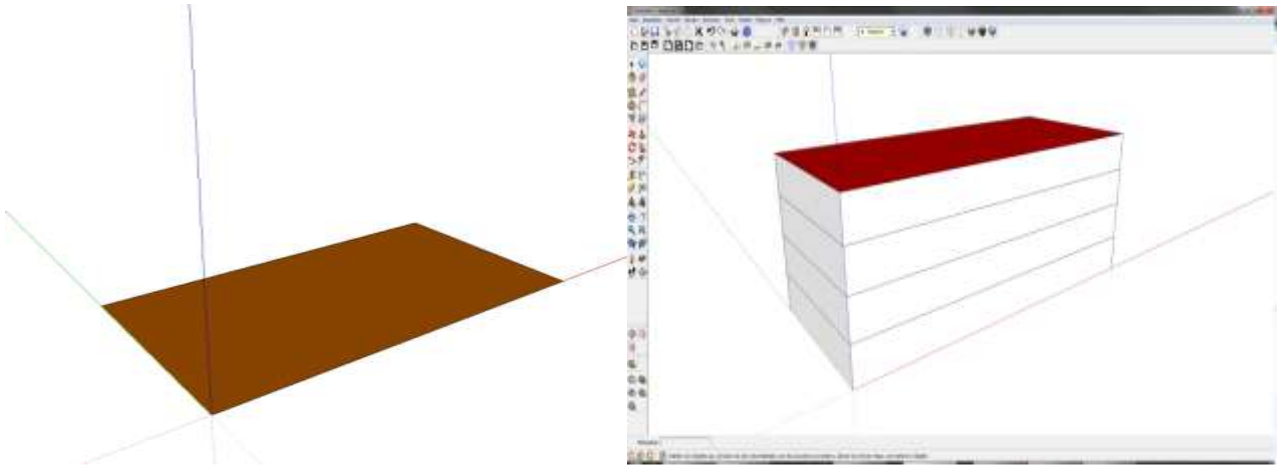

Fig. 1: The first step is for the designer to define the footprints on a projected level plane or an existing environment (left). In the second step, the footprints can be extruded to create volumetric models (right).

5.2 Structural generation

When the designer has found a satisfying arrangement for his conceptual volumes, the optimization of the parametric FSDM can be started. The structure generator then optimises the parametric FSDM using a genetic algorithm. This algorithm is set up to find near optimal solutions in a short time. In our case, it needs up to two seconds for a four-storey building (see also [9]).

Let us introduce the major properties of steel-structured buildings to show the application of these in our presented method. The ceiling systems of steel-structured buildings are usually composed of slabs and beams. For small spans, it is possible to use Slim Floor ceilings with integrated steel beams. The advantages of this design include low construction heights and unrestricted space for installations. This has a positive effect on the floor height and consequently on the facade surfaces and the volume of the building that has to be heated. The ceiling beams are often designed as welded steel profiles with a wider bottom flange for supporting the slabs. Beam-supported slab systems are suitable for larger spans as they allow a more flexible floor plan. Cellular beams facilitate the routing of the installation wiring. Steel columns are normally used for office and administration buildings consisting of steel and steel composite structures. H-profile columns encased in concrete and concrete-filled hollow sections are installed where there are heavy loads to be supported, fire protection requirements to be fulfilled or design criteria to be met.

In the concept presented here, construction components are optimized primarily from the point of view of design criteria, ecology and economy. For beam-supported slab systems, for instance, the spacing of the beams should be optimized in such a way that both the slabs and the steel beams fulfil the sustainability criteria to the highest possible extent. To this end, the construction components will be analysed from an ecological and an economic point of view. Increasing the span of the slab and, consequently, the distance between the steel beams calls for thicker slabs, which in turn incurs higher costs per square meter. The higher the material input, the lower the ecological quality. Conversely, increasing the distance between the beams decreases the number of steel beams required. This has a positive effect on the amount of resources and the costs involved. These savings are partly offset by the extra burden incurred by the thicker slabs.

After this optimisation the tool provides instant feedback on architectural design variants with ecologically optimized steel composite systems for the building blocks. To visualize the results, the system uses an abstract structure representation in SketchUp that provides information on the required spacing for structural systems and elements.

5.3 Automated Design Space Exploration.

To assist the designer in performing the DSE, a tool is provided to visually explore the design space and examine individual solutions. In addition, key performance indicators are displayed to support performance-oriented design (see Fig. 2). In further steps, the design can be adapted according to the visual feedback of the tool.

After adapting the design, the structure generator can be started again. This iterative process can be continually repeated until the final solution is found. This solution can be exported for reuse and refinement in the following planning phases.

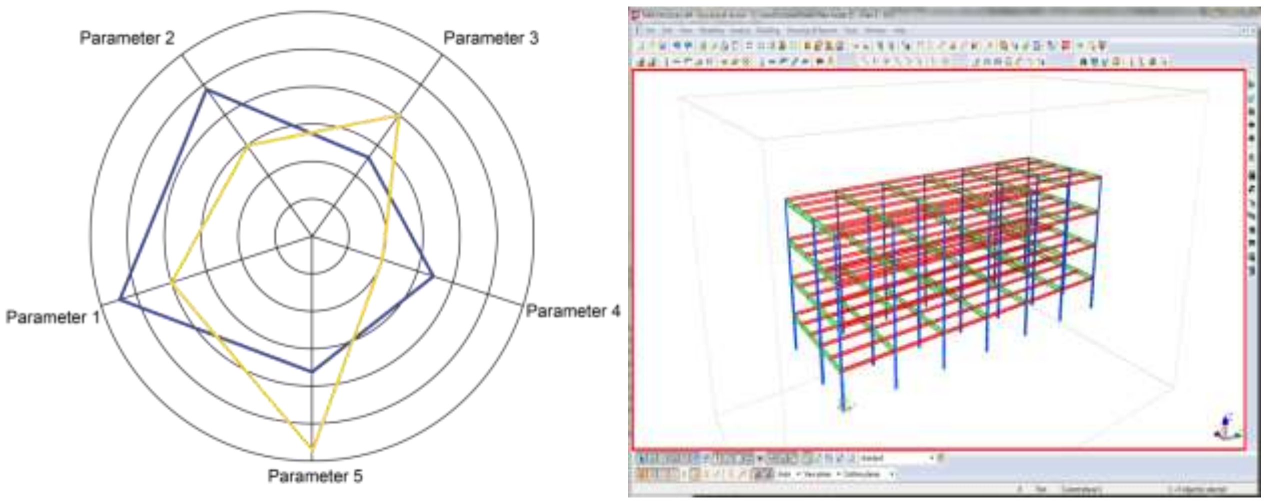

Fig. 2: The key performance parameters like costs or global warming potential will be displayed (left) by way of feedback. To support further discussions with other specialist engineers involved in the project, it is possible to export the generated structural models into other applications (right).

6. Outlook

In further development stages, we plan to include the influence of technical (i.e. HVAC) systems in our investigations. According to our experience, these systems have a high impact on both energy use and on the space needed for installation.

We also intend to extend the material database to include other materials, such as concrete or wood. This is essential for evaluating the sustainability of a building, since it is possible to compare the different materials and related structural systems during the conceptual phase in order to choose the best option. Furthermore, the material selection for the structure has a high impact on the construction cost.

7. Conclusion

This paper addresses the challenges faced today when creating a building design. It shows the importance of assisting designers in the initial design stages, in particular when it comes to sustainable building design. Sustainability is a complex and highly interdisciplinary topic. However, in many cases the interaction with the specialist engineers only commences after major decisions have been taken. They can then only maximize sustainability within a limited range, since the most fundamental, major decisions have already been taken.

The main criteria have been introduced in order to counteract this phenomenon. We have furthermore introduced an approach on how to implement expert knowledge into the early design phases. This is the backdrop behind the Automated Design Space Exploration tool. It is a computer-aided search for well-performing solutions from among all the possible solutions available, the design space.

Finally, we have described the implementation of a software prototype to illustrate how the presented concept can be incorporated into a design environment. There is still a great deal of research left to be done, however, most of it focused on integrating other aspects of building design (such as facades, mechanical and electrical engineering etc.) and other materials for the supporting structure (like wood and concrete).

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