THE DESIGN SPACE EXPLORATION ASSISTANCE METHOD: CONSTRAINTS AND OBJECTIVES

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ABSTRACT: *In the early design stages of buildings, architects cope with a multitude of decisions that affect the later performance of the building. Most of these decisions have a fundamental impact on the building design; later changes are impossible or require a very high effort. When taking these decisions, numerous constraints and objectives have to be considered. With today's mainly manual design workflows, only very few design options can be elaborated and evaluated against the various performance criteria. In consequence, the design space (the space of all possible design options) is explored only to a very limited extend and finding a good solution depends strongly on the experience of the designing architect. To cope with this issue and to better support architects in the early design stage, we are developing the Design Space Exploration Assistance Method (DSEAM). The method aims at applying techniques of advanced computation to provide comprehensive information and design options. To provide a sound foundation for this method, this paper investigates how relevant and evaluable the individual objectives and performance criteria are. In addition, we discuss the importance of geometric constraints in building design and describe an approach which allows architects to define them in an intuitive interactive graphical manner.*

KEYWORDS: *Design Space Exploration, Conceptual Design, Optimization, Decision Making*

1. INTRODUCTION

In the last decades, the design of new buildings has become an increasingly complex process, in which different goals have to be fulfilled involving various experts. Whereas before only functional criteria and the appearance of the building were criteria, nowadays the focus shifts to energy efficiency and sustainability. The designer needs to take into account resource consumption and a lot other technical criteria during the design process. In this context, designing a building is a highly complex and challenging task, that interconnects architectural design closely with engineering. A well-designed building has to meet many different requirements, i.e., it must be a solution that fulfils its function well, has good appearance and spatial qualities, has a sound structural system, provides a pleasant indoor climate, has an energy and resource efficient design and complies with the clients requirements such as cost budget. Accordingly, the building design process is of complex nature involving a large number of decisions and iterations.

Today this complex decision-making process is mainly conducted informally and on the basis of experience, often resulting in sub-optimal solutions. If, however, computer tools assist the process, better performing design options may be found. Such assistance has the highest impact in the early design stages, where fundamental decisions are taken and modifications are easy.

Though many research projects in the field of assisting conceptual design by design space exploration (DSE) have been performed in recent years, the developed approaches did hardly find their way into industry practice. This is mainly due to the fact that most of the available tools are complex, require a deep mathematical understanding, and can thus not be intuitively operated by architects.

To cope with this issue, an approach to integrate expert engineering knowledge into architectural conceptual design, the Design Space Exploration Assistance Method (DSEAM), is proposed in this paper. DSEAM helps architects to systematically investigate different design options and find well-performing solutions. This is achieved by providing means for evaluating preliminary designs with respect to design objectives, such as structural performance, energy and resource efficiency, and integrating an automated design space search, which provides suggestions for improving the design.

This paper tackles the translation of the technical and functional requirements, design intentions as well as the criteria of sustainability into computable models in order to allow the automated search. In this paper, the criteria of the DGNB (Lemaitre C. and Deutsche Gesellschaft für Nachhaltiges Bauen 2012) provide the basis, however,

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having in mind the translatability to other criteria systems, such as LEED (2009) or BREAM (2008). This translation requires the formulation of requirements and intentions as objectives or constraints. However, those models are by far not able to capture all relevant criteria. Therefore, different strategies of interactivity are required to manage the criteria. For some, e.g. energy consumption and related cost, an automated search works well as they depend on simple physical interdependencies such as thermal transmission through insulation. For other, e.g. the distance of columns in a building structure, an interactive approach is required as there are functional considerations of the use in the building and of the appearance of the façade determined by the column grid. This decisions only an architect is able to carry out, because it relies on tacit knowledge which cannot be described explicitly.

Therefore, the paper first examines typical constraints following a common course and interactive character of a design process. Second, the translation and evaluation of criteria of sustainability aims at proving assistance for sustainable design. As a representative method, this paper uses multicriteria design optimization for developing the DSEAM. Furthermore, as proof of concept, a prototypical software tool has been implemented which provides an intuitively usable, interactive interface as part of an existing and commonly used design environment.

In the first step, the tool supports the design of regular office and administrative buildings. There are two reasons for this decision: On the one hand this kind of buildings normally have a regular shape. The building itself as well as the office spaces are often of rectangular shape. On the other hand, there exist many regulations for these kind of buildings, like working space guidelines, fire safety regulations and specific green building certificates like LEED, BREAM and DGNB, which are examined in this paper.

2. STATE OF THE ART

Automation approaches applied for DSE in research and application in building design are either general studies for building types that do not consider the specific situation of the individual design case with its environment; or there exist specifically tailored solutions for single design case instances.

For example, the computer program Rt by Mahsuli and Haukaas (2013), that focus on multi-model analysis, addresses the need for tools to carry out modern reliability and optimization analyses.

The H.D.S. Beagle 1.0 is a tool developed by Gerber et al. (2012) that combines parametric modelling (Autodesk Revit 2013) with energy analysis (Autodesk Green Building Studio 2013) and cost prediction (Microsoft Excel 2013) in a genetic algorithm (GA) optimization. Another tool on the basis of Autodesk Revit is the Design Performance Viewer developed by Schlueter and Thesseling (2009).

Gane and Haymaker (2012) have developed a new method, the Design Scenarios (DS) to collect and manage the requirements of multiple stakeholders to enable an alternative generation, analysis and decision making process on the basis of parametric CAD tools.

A method to convert set grammars into parametric models and calculate their energy demand is presented in Granadeiro et al. (2013). With this approach, many different shapes of a building can be generated automatically and then be translated into a simulation model to calculate energy demands.

Mensinger et al. (2012) developed a tool using GA to generate and optimize steel and steel composite structures in terms of sustainability. Fernandez-Ceniceros et al. (in press) have developed a model to for finding the best one-way floor slab design regarding embodied CO2 and cost including construction and transportation costs. Shi & Yang (2013) coupled Rhinoceros/Grasshopper with the performance simulation programs Ecotect, Radiance and Energy Plus to establish the workflows for performance-driven architectural design and optimization.

A framework for automated LEED certification based on cloud-BIM is presented by Wu et al. (2012). They propose to couple BIM-software and mobile BIM-apps to a central Multicore BIM Server to automatically extract the necessary information to load it on the LEED Automation Cloud.

A framework that copes with a multilevel optimization is the Bi-Level Integrated System Synthesis (BLISS, Sobieszczanski-sobieski et al., 1998). This hierarchical approach of using optimization provides foundation for partial optimization problems within user interaction.

Despite these important research works, an approach that assists architects with finding well performing solutions in the early design stages is still missing. A methodology is required which allows to assess initial building designs with respect to energy efficiency and sustainability. Corresponding assistance methods have to be available right in the design tool they use for modelling the geometry and further building information. It has to combine the manual design space exploration with assisting optimization approaches presenting well performing solutions to the architect to explore the design space and to decide on the solution. These optimization approaches will be strongly related on existing methods; only few will be implemented newly. The new method focuses on providing the methods in the design tool. Nevertheless, the Building Information Modelling (BIM) process will be supported through making the results of the DSEAM available to serve as a basis for discussions between the involved designers and engineers and further refinement in downstream applications.

3. ASSISTANCE IN THE WORKFLOW

Assistance in the workflow means that the computer tool, i.e. optimization does not prescribe the "optimal" design solution but gathers information on well-performing solutions to allow the designer to select from. There are two major reasons, why not just one best solution is demanded; on the one hand, the automatic generation and search of the well performing solutions has to be fast. On the other hand, an optimization is not able to find the real optimum, because not all relevant objectives can be integrated directly due to tacit knowledge and non-numerical criteria. Maybe the optimum design for the whole building not includes the optimum design of e.g. the structural materials because of interactions to other disciplines. So only with the fast feedback of well performing solutions, the architect can explore many different variants and therefore will find the overall best performing design.

We see this process as a hierarchical optimization problem similar to the BLISS approach. However, the main difference is that the top-level is not an automated optimization but an interactive process. The architect creates the first drawings on a blank paper and respectively simple models in the computer. Then in a dialogue, these models are changed due to performance or other feedbacks from clients or expert engineers. In the presented approach, the architect creates the initial design in a CAD program and then can adjust it according to the feedback of the DSEAM. The result a design flow of optimization that is structured into two loops as described by Geyer (2009). The inner loop serves the DSE and provides the performance information. Given a computable model of the performance depending on the degrees of freedom (design variable and structure-changing variants), automated techniques of DSE can be applied.

Since not all objectives and constraints can be translated into computer understandable models, the evaluation of the design cannot be completely automated. Therefore, the outer loop consists in an interactive process developing the design. The architect evaluates the non-computable aspects and selects solutions of the broad range of computer-generated suggestions or develops the models further and starts a new round of the inner cycle. Therefore, all design variants are displayed within the CAD System and can be explored in a computer environment commonly known by architects.

4. CONSTRAINTS

Due to their character, constraints split into two categories. The first category is numeric and thus is well expressible by the mathematical form, as it is usual for optimization:

$$g(\mathbf{x}) \leq 0. \tag{1}$$

The function g describes the numeric constraints to comply with depending on the design variables $\mathbf{x}$. For instance, such a constraint can implement a minimum distance between columns or the maximum investment cost of a project in the DSE by such a constraint. As these constraints are explicitly set up as formula, we call them explicit constraints. Furthermore, constraints can form a hard limit, such as a fixed financial budget not to be exceeded, or soft and discussable boundaries, such as the ratio of room depth and room height; in the latter case, an exceeding is awarded with a penalty. To implement this difference, several functions are available translating these constraints, in the first case, to barrier functions not to be exceeded or, in the second case, to penalty functions, which can be exceeded for certain costs, as discussed by Papalambros & Wilde (2000, Chapter 7.6).

The second category describes constraints that are non-numerical and exhibit a qualitative or structural character. The choice of elements and how they are linked, i.e., the structure of the model represents such constraints. As these constraints usually rely on tacit knowledge that is difficult to express as formula explicitly, we call them implicit constraints. For instance, selecting tubular structure integrating the stairs and the elevator to absorb the lateral loads instead of three shear walls results from tacit knowledge on the organization of floor plans and their flexibility. These implicit constraints are an important means to define the design case as optimization problem for DSE. They closely relate to the usual interactive way of modeling in building design, as the designer sets them interactively during the modeling process. Therefore, the transfer of the interactive modeling to the definition is of major importance as it is described in the following sections.

The information for design optimization has to be taken from the architects' graphically entered CAD model. It can be either available directly in the model, derived from the model data, like geometry data (areas, volumes, surface areas …) or determined as design intent (wall type from wall thickness or windows size from further definitions), and finally, automatically generated (Sanguinetti et al. 2012). To get as accurate as possible, this requires objects of modeling that include the necessary definitions (semantics) to define the constraints. Environments of Building Information Modelling (BIM), such as Autodesk Revit (2012) partly provide the necessary semantically rich objects. However, the extension by objects specific for the definition of optimization problems is required to describe the design with its limiting requirements and its design space for DSE.

4.1 Objects to interactively define constraints

According to the concept of implicit constraints, one important element are appropriate elements to define the functional or aesthetic constraints of the design case in such a way that the essential requirements and characteristics are captured but the latitude for DSE is available. This section proposes some modified elements for interactive CAD environments.

4.1.1 Conceptual Volumes

Within the CAD environment, the architect can work with two different types of conceptual volumes, which represent the recent evolution of the design within the design process. In the very beginning, the architect thinks about how to fit the building's volume in the environment and that it must not exceed the local restrictions like plot boundaries and maximal building heights (Figure 1). In this stage the blocks represent the outer shell of the building. Also setback storeys on top of the building can be modelled.

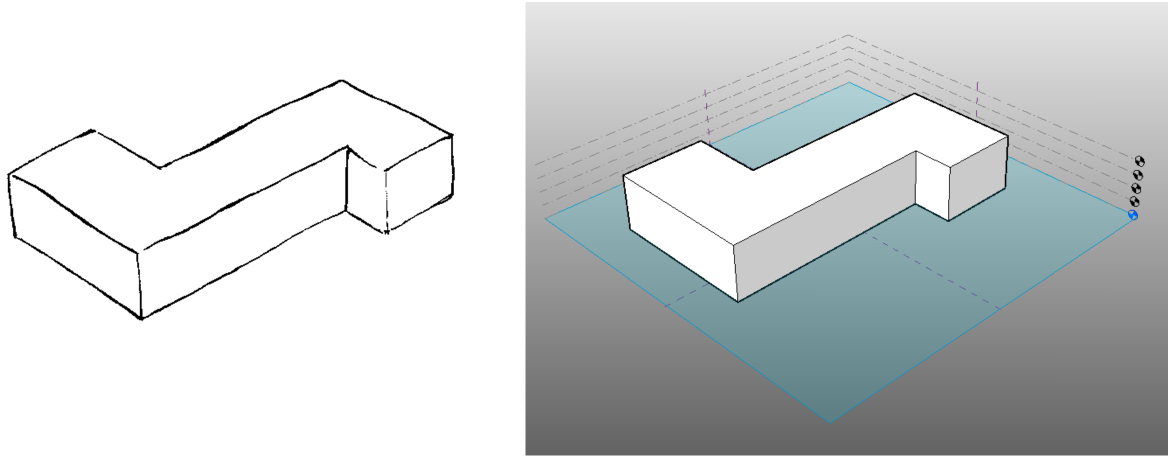

Fig. 1: Conceptual Volume as hand drawing (left) and as a 3D-modell in a CAD tool (right).

If a satisfying arrangement is found, the architect can divide the blocks into sub-volumes which represent the usage areas of the building like office spaces, horizontal and vertical access areas, entrance area, social spaces etc. Forces are added accordingly to the use of the area. Furthermore, the different storey can be defined by global horizontal levels (Figure 2). In this stage of the design, the arrangement of the rooms is not taken into consideration. The finest resolution of the spaces is the usage areas.

4.1.2 Façade

For the façade-system itself only basic parameters are adjustable. After the architect has defined a façade system (like full/structural glazing or punctual façades), the range of percentage of glassing is defined by the selected system itself (design intent). For the glass itself, the overall heat transfer coefficient (U-factor), the Visible Transmittance (VT) and the costs can be chosen in steps from low to high in the properties of the façade. With this information structure, the architect doesn't need to think about the exact values in this early design stage. The constraints are generated automatically according to the basic definitions.

Furthermore, it allows the tool to choose from a higher amount of options that are stored in an internal database and can be updated without affecting the appearance of the tool itself. For the opaque parts of the facades the U-value and the costs can be defined in the same way as described above.

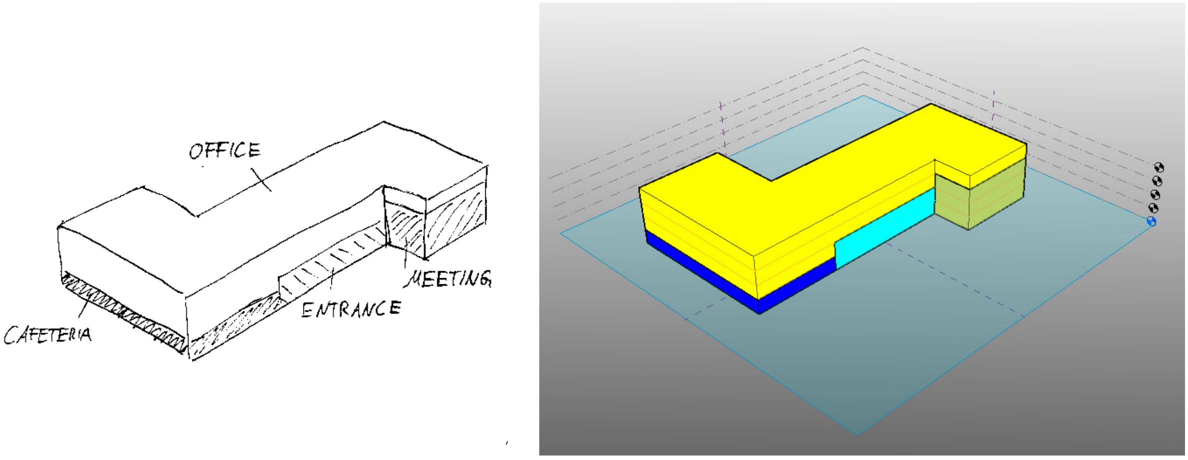

Fig. 2: Conceptual mass divided in the different usage areas entrance, meeting, office and cafeteria spaces in a conceptual sketch (left) and as masses in a CAD tool (right).

4.1.3 Structure

To generate the structural work automatically further information is required. The number of floors, defined by horizontal levels, and the dimensions of the building are given by the input of the architect and therefore can be derived from the model. The vertical loads can be determined as design intent according to the usage areas.

5. OBJECTIVES

To assess a proposed respectively generated design solution, it is required to apply a scheme of evaluation criteria. These criteria form the basis for the objectives; the objectives aggregate one or more criteria, e.g., by the weighted-sum method as it is practiced by the DGNB system. By allowing more than one aggregation the definition can form a multi-criteria problem, for instance, according to the major categories of sustainability ecologic quality, economic quality, and sociocultural and functional quality; also the addition of individual objectives according to the wishes of the client, designers etc. is possible, which is not discussed here.

As our approach focuses on sustainability and its computer support, this section examines indicators given by the DGNB certification system as criteria for the use with the DSEAM. Considering the automated DSE, the objectives split up into three categories:

(1) On the one hand, there are criteria that the search method can evaluate automatically without any intervention of the designer; an example are the environmental impacts of materials (e.g. emission of gases being harmful to climate) in case the BIM-based model includes all material definitions and a comprehensive data base is available.

(2) On the other hand, for a part of the criteria, no automated evaluation is possible and an expert assessment is required. For instance, the flexibility and the effort for, e.g., changing the building technology are especially in early phases only assessable by an expert. The strategy in this case is to define the desired level of flexibility and to include this definition as implicit constraints, such as a configuration of vertical shafts, or as explicit constraints, such a minimum height for ceiling installations, in the DSEAM.

(3) A third category includes criteria that need only some interventions. They require a combination of measures for implementation in the DSEAM. Construction costs are an example. The quantity determination is already automated very well. However, the estimation of the specific costs of one kind of construction in a specific situation requires the experts' experience.

The following sections discuss the indicators of sustainability and its use as objectives in the DSEAM in detail. The objectives for the automation are taken from the German DGNB (Lemaitre and Deutsche Gesellschaft für Nachhaltiges Bauen 2012). But since the early design stage of a building addresses not all of the DGNB criteria, the relevant objectives are named.

5.1 Eco-balancing – emission induced environmental impacts (ENV1.1)

The criterion "ENV1.1 Eco-balancing – emission induced environmental impacts" of the DGNB uses the following environmental impacts:

- Global Warming Potential (GWP) in kg CO_2-equivalent

- Ozone Depletion Potential (ODP) in kg R11-equivalent
- Photochemical Ozone Creation Potential (POCP) in kg C_2H_4-equivalent
- Acid Potential (AP) in kg SO_2-equivalent
- Eutrophication Potential (EP) in kg PO_4-equivalent

The components that have to be considered are listed according to DIN 276, which requires modelling representing building parts such as walls, columns, slabs etc. As these elements are not completely included in the early design phase, further assumptions and approximations are required. Furthermore, transport and site products and installation processes are not included in the DGNB objectives that would be hard to provide at this stage of the development of the building.

In the use phase, the energy consumption of the building is calculated on the basis of the German EnEV (2009), and DIN V 18599 (2011). Therefore, many tools already exist that can be included for an overall calculation of energy consumption for the different usage areas defined by the architect. But these tools often lack the need for exchange formats to run the calculation without generating a specified model from scratch.

Furthermore, the costs and energy consumption for maintenance and replacement of building components and the materials it consists of is stipulated by DGNB. This is mainly not calculable because exact knowledge of the use of the building, the arrangement of rooms or inner walls and technical installations is required, which cannot be delivered in the conceptual phase.

To calculate the impact on eco-balancing at the end of the building life cycle, following materials have to be distinguished: metals, mineral materials, materials for thermal use, materials that need to be deposited and mechanical systems.

5.2 Eco-Balancing – Primary Energy (ENV2.1)

The primary energy consumption for building operation is calculated on the basis of the German EnEV (2009), which is possible automatically to a high degree (Schlueter and Thesseling 2009). The system boundary has to be defined consistent and the period under consideration is fixed to 50 years.

The calculation is based on:

- The components (All used materials for structure and mechanical systems)
- The related processes.
- Energy consumption during the use of the building. The energy for the user specific equipment is not taken into consideration.

To calculate the impact on eco-balancing in the end of the building life cycle, the materials have to be distinguished as in ENV1.1 (see above).

The data has to be taken from the Ökobau.dat (2012) or the EPDs (2012). If the data is taken from somewhere else it has to be punished with an addition of 10%. It is based on a reference building method.

5.3 Use of Space (ENV2.3)

The criteria of space usage for the building are calculated on the basis of the use before it has been built. It rewards the reuse of industrial or polluted areas and punishes use of green areas. In this particular case the ecological compensation area is always calculated like unpolluted open space is used.

5.4 Building life-cycle costs (ECO1.1)

Costs are normally included as explicit constraint, either with or without a penalty function. In the presented approach, the costs are considered as objectives and therefore are not restricting the solutions if the desired amount is exceeded. This is necessary, because in some cases it might be suitable to exceed the costs slightly to achieve a better design.

Furthermore, costs are included not only for the construction, but as well for usage, maintenance and demolition of the building. The later retrofitting of the new building is considered as well, since it influences costs when the use of the building has to be changed (costs for construction, time when building cannot be used etc.) as well as on the sustainability, because of the materials that are exchanged during retrofitting.

The costs are estimated using the Present Value Method in the simplified procedure presented in the DGNB (Lemaitre and Deutsche Gesellschaft für Nachhaltiges Bauen 2012), including structural systems, HVAC-systems, supply and disposal costs, costs for cleaning and caretaking and costs for service and maintenance of the building.

5.5 Flexibility (ECO2.1)

For the definition of the flexibility the existing criteria are: the area efficiency factor, the storey height and the building depth. Furthermore, the categories for the use of space within the building can be evaluated like vertical escape routes per storey, number of sanitary installations, structure should use non-bearing inner walls and the structure itself should be oversized and HVAC-systems should be exchangeable easily.

5.6 Thermal Comfort (SOC1.1)

The thermal comfort has to be proofed for both the heating and cooling period. However, additional information on the use and design of the façade and the building equipment is required, which is often not available in early design phases. Typical indicators are the operative temperature, draught, relative temperature asymmetry and floor temperature, and relative humidity.

5.7 Analysis of criteria

The criteria described above are relevant ones for conceptual design. Finally, the criteria have to be evaluated, if they can be analysed automatically or require user intervention and which prerequisites have to be given. The classification is given in Table 1. Since most of the criteria are in category (3), it can be seen that for finding the best performing solution a strong interaction with the user is required.

Table 1: Categories of the different criteria

Criteria	**Category**	**Prerequisites**
ENV1.1: Eco-balancing – emission induced environmental impacts	(1) Automatic	model contains all information for the materials; connection to a comprehensive database; HVAC system for use phase.
ENV2.1: Eco-Balancing – Primary Energy	(3) Semi-Automatic	model contains all information about materials; connection to comprehensive database; User interaction needed for: energy consumption in using the building; processes related to construction.
ENV2.3: Use of Space	(3) Semi-Automatic	ecological compensation space on the basis of former unused space; further specification needs user's knowledge.
ECO1.1: Building life-cycle costs	(3) Semi-Automatic	model contains all information about material costs; user needs to asses specific costs; cleaning calculated per squaremeter; service and maintenance costs
ECO2.1: Flexibility	(3) Semi-Automatic	Area efficiency factor, storey heights and building depths can be checked automatically; all other values need user input.
SOC1.1: Thermal Comfort	(1) Automatic	model containing all information about materials and HVAC systems used.

6. GENERATION OF WELL PERFORMING SOLUTIONS

After the architect has defined the first idea using the above described elements, the DSEAM will perform the automatic generation and search of solutions. It consists of an outer and several inner loops. The architect is working in the outer loop, the inner loops serve for different subordinate optimizations: geometric, energetic, structural/topologic, costs, etc. These are the dimensions of the Design Space that the architect can explore in the outer loop.

The DSEAM modifies the geometry within the boundaries defined by the architect, e.g., the building can be moved on site, get shorter but higher or lower and wider. The orientation is not modified because in most cases it is fixed due to external restrictions (like other buildings or infrastructure) where the entrance areas, offices and other usage areas are aligned to. Furthermore, there is no optimization of floor plans included in the manner of the new arrangement of rooms. The usage areas are used to calculate the minimal floor height needed for the use, if the required daylight-factor is achieved and if the evacuation routes do not exceed the required length.

The HVAC components can be defined for a usage area for the whole building from predefined regular systems. The computation in this stage consists of e.g. the heating/cooling power needed for whole building, calculation of solar loads, area/volume ratio, and façade area. Further simplified models of comfort will be included that do not use simulation due to modeling effort and quick response.

Modifications by the DSEAM here are e.g. a rearrangement of the usage area within a certain field and an adjustment of the storey heights to find an optimal solution for the structure of the building and fulfil all constraints from local laws like minimal room heights according to the use and maximum escape route lengths. The material of the structure is automatically generated and modified by the DSEAM. At this stage the material is not fixed due to find the optimal use of resources for the structure.

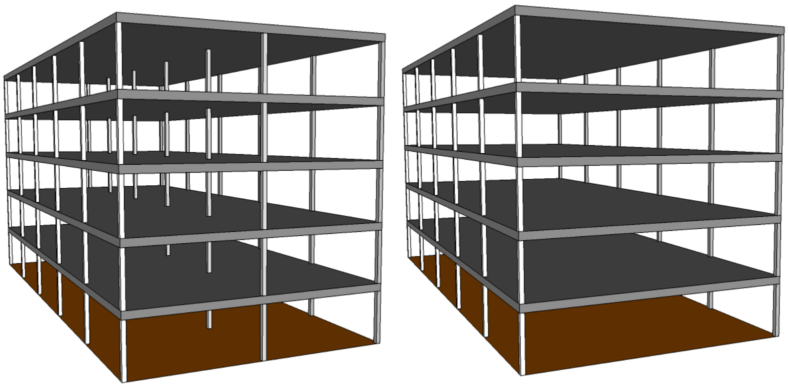

Fig. 3: Before the generation and calculation the architect can define if columns should be used within certain spaces. The columns would then be placed (left) or not (right) affecting other structural elements like slabs and the columns in the outer rows.

The areas for the structure are computed according the conceptual volumes for the different usage areas and additional information, such as if it is possible to place columns in an area or a column free space is required (Figure 3).

Costs for the materials, processes and energy use is summarized. With this, the architect is enabled to understand the influences of decisions for the whole building life cycle.

The well performing solutions are then selected by the DSEAM and then displayed as in Figure 4. The architect can explore the different solutions and select and if necessary modify the preferred solutions. After every modification the automatic search can be started again, until a satisfying solution is found.

7. CONCLUSIONS

In the early design stages, architects have to cope with a huge design space that cannot be explored manually without a great experience by the architect. But this is necessary because of its high impact on the later performance of the building. The Design Space Exploration Assistance Method (DSEAM) is a new approach, which enables architects to explore the design space more easily. It combines an automated search for well performing solutions with the non-computable tacit knowledge of the architect in an interactive process.

Therefore the different objectives that are important in the early design stages are named in this paper and split in three categories; (1) automatic, (2) non-automatic and (3) semi-automatic i.e. only some user interaction is required.

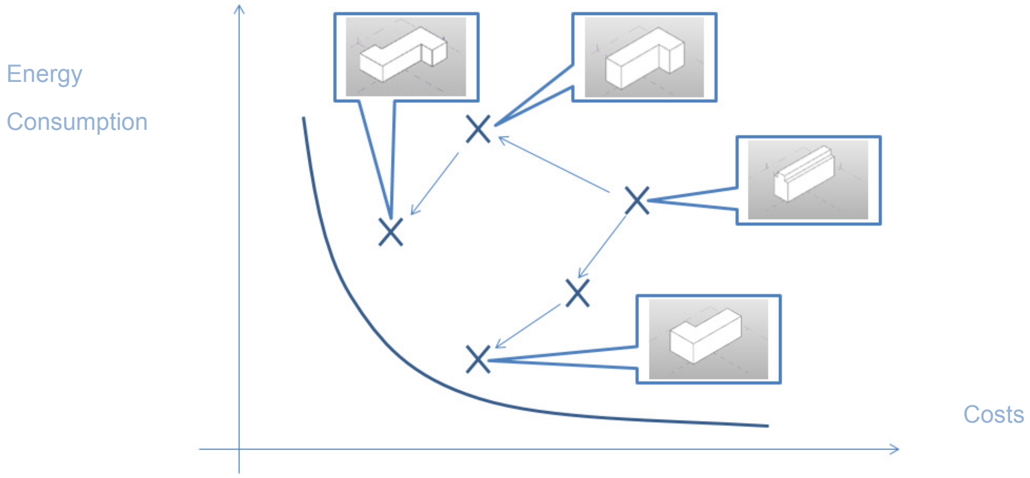

Fig. 4: After the automatic generation and search for well performing solutions, the architect can explore the different variants manually (here for a two-dimensional design space).

For the non-automatic part, the DSEAM is implemented in a CAD tool, to integrate the new approach in an interactive modelling environment common to most architects. Though they do not have to switch their kind of working to use the DSEAM. The automated part of the DSEAM consists of different analysis, namely (1) geometric (2) energetic (3) structural/topologic and (4) costs and methods of DSE, for which in this paper optimization was chosen. The analysis is relying on the definitions of the DGNB (Lemaitre C. and Deutsche Gesellschaft für Nachhaltiges Bauen 2012) to enable sustainable design from the very beginning of the planning process.

There are two major limitations in this process. On the one hand, that the databases for the building materials in terms of sustainability are not complete i.e. many materials are missing or cannot be calculated yet which has influences on the number of solutions calculated and may exclude better ones. On the other hand, there are some deficits in calculation since due to calculation speed not all parts can be included (like welding work or screw for connecting bearing parts) which will reduce accuracy compared to the outputs of the final design.

Further steps of the development are elements for interactive modeling, the design process and the graphical interface for the exploration of the solutions including the visualization of the different solutions of the inner cycle. Furthermore, an export format has to be developed that enables the further use of the generated information.

8. REFERENCES

Autodesk Revit (2013). Revit 2014, *Autodesk, Inc.*. Available at: http://usa.autodesk.com/revit/.

Autodesk Green Building Studio (2013). Green Building Studio, *Autodesk, Inc.*. Available at: http://www.greenbuildingstudio.com.

BREEAM (2008). BRE Environmental Assessment Method, *Building Research Establishment (BRE)*. UK. Available at: http:www.breeam.org

DIN V 18599 (2011) Energetische Bewertung von Gebäuden, Bundesamt für Bauwesen und Raumordnung (BBR)

EnEV (2009). Verordnung über energiesparenden Wärmeschutz und energiesparende Anlagentechnik bei Gebäuden (Energieeinsparverordnung – EnEV 2009). Available at: http://www.enev-online.de/.

EPD (2012). Environmental Product Declaration, *Institut Bauen und Umwelt e.V. (IBU)*. Germany. Available at: http://bau-umwelt.de/hp474/Umwelt-Produktdeklarationen-EPD.htm.

Fernandez-Ceniceros, J., Fernandez-Martinez, R., Fraile-Garcia, E. and Martinez-de-Pison, F.J. (in press). Decisions support model for one-way floor slab design: A sustainable approach, *Automation in Construction*, Vol. 0, No. 0. Available at: http://www.sciencedirect.com/science/article/pii/S092658051300099X.Gane V. and Haymaker J. (2012). Design Scenarios: Enabling transparent parametric design spaces, *Advanced Engineering Informatics*, Vol. 26, No. 3, 618–640. Available at: http://www.sciencedirect.com/science/article/pii/S147403461200047X.

Gerber D.J., Lin S., Pan B. and Solmaz A.S. (2012). Design optioneering: multi-disciplinary design optimization through parameterization, domain integration and automation of a genetic algorithm, *Proceedings of the 2012 Symposium on Simulation for Architecture and Urban Design,* Society for Computer Simulation International, San Diego, CA, USA, 11:1-11:8. Available at: http://dl.acm.org/citation.cfm?id=2339453.2339464.

Geyer P. (2009). Component-oriented Decomposition for Multidisciplinary Design Optimization in Building Design, *Advanced Engineering Informatics.* Vol. 23, No. 1, 12-31. Available at: dx.doi.org/doi:10.1016/j.aei.2008.06.008.

Granadeiro V., Duarte J.P., Correia J.R. and Leal V.M. (2013): Building envelope shape design in early stages of the design process: Integrating architectural design systems and energy simulation, *Automation in Construction*, Vol. 32, No. 0, 196–209. Available at: http://www.sciencedirect.com/science/article/pii/S0926580512002415.

LEED (2009). Leadership in Energy and Environmental Design, U.S. Green Building Council. Version 3. Available at: http://www.usgbc.org/leed.

Lemaitre C. and Deutsche Gesellschaft für Nachhaltiges Bauen (2012). *Neubau Büro- und Verwaltungsgebäude: DGNB Handbuch für nachhaltiges Bauen; Version 2012,* Deutsche Gesellschaft für Nachhaltiges Bauen. Available at: http://books.google.de/books?id=1kdOMwEACAAJ.

Mahsuli M. and Haukaas T. (2013) Computer Program for Multimodel Reliability and Optimization Analysis, *Journal of Computing in Civil Engineering*, Vol. 27, No. 1, 87–98.

Mensinger M., Huang L., Zhang P. and Hogger H. (2012). Optimization of sustainable office buildings in steel using genetic algorithms, *Proceedings of the Nordic Steel Construction Conference 2012*, Oslo, Norway.

Microsoft Excel (2013). Excel, *Microsoft Corporation*. Available at: http://office.microsoft.com/en-us/excel/.

Ökobau.dat (2012). Ökobau.dat 2011 v5, *Bundesministerium für Verkehr, Bau und Stadtentwicklung.* Germany. Available at: http://www.nachhaltigesbauen.de/oekobaudat/index.php.

Papalambros P.Y. and Wilde D.J. (2000). *Principles of Optimal Design: Modeling and Computation,* Cambridge University Press, New York, NY, USA.

Sanguinetti P., Abdelmohsen S., Lee J., Lee J., Sheward H. and Eastman C. (2012) General system architecture for BIM: An integrated approach for design and analysis, *Advanced Engineering Informatics*, Vol. 26, No. 2, 317–333. Available at: http://dx.doi.org/10.1016/j.aei.2011.12.001.

Schlueter A. and Thesseling F. (2009). Building information model based energy/exergy performance assessment in early design stages, *Automation in Construction*, Vol. 18, No. 2, 153–163. Available from: http://www.sciencedirect.com/science/article/pii/S0926580508001064.

Shi X. and Yang, W. (2013). Performance-driven architectural design and optimization technique from a perspective of architects, *Automation in Construction*, Available at: http://www.sciencedirect.com/science/article/pii/S0926580513000253.

Sobieszczanski-Sobieski J., Agte J.S. and Sandusky R.R. (1998). Bi-Level Integrated System Synthesis (BLISS), *NASA Langley Technical Report Server.* Available at: http://arc.aiaa.org/doi/pdf/10.2514/6.1998-4916.

Wu W. and Issa R. R. A. (2012). Leveraging Cloud-BIM for LEED Automation, *ITcon*, Vol. 17, 367-384. Available at: http://www.itcon.org/2012/24.