NordDesign 2016
August 10 – 12, 2016
Trondheim, Norway

Planning and developing Adaptive Buildings require methodical support

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Abstract

Adaptive Buildings are an approach for realising the next generation of buildings. Here, the idea is to actuate the structure and the building envelope using sensor/actuator systems for a high level of lightweight design and to increase the feeling of comfort. The support structure of a building is dimensioned for stresses that probably only occur once in their life cycle, e.g. during an earthquake. Besides these special events, the structure is oversized. As an improvement and to increase the level of lightweight design, sensors could measure tensions in the support structure and actuators could decrease the stresses immediately. With the actuation of the building envelope, it is possible, for example, to control the permeability of its facades in order to influence thermal characteristics like temperature or the humidity of the interior. In both cases, the behaviour of the elements becomes dynamic. Research is therefore conducted into how and where the sensors – and the actuators in particular – have to be integrated.

Changes in the construction industry are necessary because a significant proportion of the world's resources and produced energy are used by it. The feasibility of the approach of Adaptive Buildings has already been proven in several studies, e.g. the lightweight shell structure called "Stuttgart SmartShell".

It is obvious that the development of Adaptive Buildings requires collaboration between architects, civil engineers and mechanical engineers which had not previously existed. To manage this cooperation with regard to technical challenges, an interdisciplinary methodical procedure for planning and designing is essential. Due to the fact that a holistic methodical support process does not yet exist, such procedures have to be developed. The research question of this paper is:

What challenges exist when planning and developing more complex (adaptive) buildings and what derived requirements have to be taken into account for the appropriate methodical support?

Keywords: Design Methods, Adaptive Buildings, Mechatronics, Lightweight Design, Requirements

1 Introduction

Sustainable buildings and the integration of a high number of technical functions are current and important trends in the construction industry. Resource and energy efficiency are key characteristics of sustainable building solutions. In this regard, lightweight design of buildings and their structures becomes more important. Therefore, different strategies for lightweight design are researched in the field of architecture. These can be compared with those from aviation and automotive engineering. Henning & Moeller (2013) describe the various well-known strategies of lightweight design in product development. To significantly reduce material usage in future buildings, a new solution is required. Sobek (2000) presents the approach of Adaptive Buildings, which leads the behaviour of buildings to become dynamic. By adapting to impacting effects, the building responds to the environment using sensor/actuator systems implemented in the support structure or the respective building's envelope. Through the attendant homogenisation of stresses in the structure, it is possible to construct using less material. Later, this paper will explain the approach in more detail by using previously realised examples of adaptive elements.

The integration of technical functions already increases the complexity and the number of different specialists required for designing the building. By using the presented approach, the complexity and the planning effort increase further. The actual procedure of planning buildings is not designed for these challenges and has to be developed further for this new application area. To realise Adaptive Buildings, the planning process in the construction industry and the development process of mechanical engineering aspects have to be merged to form a new planning approach.

2 Problem statement and goals

Based on the development described in the introduction, the process of building design has to be appropriately advanced. The actual building planning processes in different countries describe several planning steps which are based on each other in each case. Until now, it has been possible to plan buildings in a sequential procedure in terms of the disciplines involved. The first main steps comprise the design drawings and the planning, conceptualisation and dimensioning of the supporting framework. The technical equipment has to be subsequently integrated. In this case, the planning of buildings requires cooperation between architects and civil engineers. The planning of taller buildings also requires cooperation with building services engineers to integrate the building services engineering.

In order to plan more complex buildings like Adaptive Buildings, the cooperation of different disciplines has to start in the first steps of the building planning process. By integrating sensors and actuators into the support structure of the building, the construction elements – for example facade elements and the support structure – have to be planned and developed in unison. The requirements of the whole building therefore have to be defined corporately by civil engineers, mechanical engineers and architects. Alongside this expected change to the planning process in the construction industry and the representatives of the disciplines involved in this, the requirements for solving the technical challenges using a methodical support have to be considered in addition to the integration of aspects of the different life cycles of these buildings. It has been demonstrated that current processes for planning buildings have to be analysed and developed further in terms of these new constraints. The key research question of this paper can therefore be stated as follows: *What challenges exist*

when planning and developing more complex (adaptive) buildings and what derived requirements have to be taken into account for the appropriate methodical support?
In this context, the superordinate goal is the analysis of the existing procedures, the presentation of the advanced and targeted concept of buildings as an initial situation and the communication of the first results for developing the planning processes of such buildings. The results primarily form the basis for the next research steps of the method's development, and additionally for the development of Adaptive Buildings in future.

3 Structure of the paper

In order to answer the research question, this paper analyses the initial situation to identify the technical and – in particular – the methodical challenges. The fourth chapter therefore summarises the results of literature research about the current procedures for planning in the construction industry and in mechanical engineering, together with related applied methods. Furthermore, to describe the environment and the technical challenges of Adaptive Buildings in more detail, the identified approaches for adaptive elements in these buildings are also presented. On this basis, the main differences between civil engineering and mechanical engineering are discussed in the fifth chapter. The sixth chapter then lists the methodical challenges and the demand for methodical support for a holistic planning process derived from these.

These aspects, which have to be considered when developing a planning process for Adaptive Buildings – including its complexity, the interdisciplinary approach of the development and cooperation as well as safety – have to be identified through literature research and discussions with researchers involved in the field of Adaptive Buildings.

4 State of the art

This chapter deals with the results of an analysis of existing planning procedures in architecture and civil engineering and the development process in mechanical engineering. Furthermore, the approach of Adaptive Buildings is presented in detail using examples of adaptive elements suited for Adaptive Buildings.

4.1 Construction planning process

The planning process in the fields of architecture and civil engineering is associated with recommended or official service phases of architects (and engineers) in the respective country (Erdell, 2006). However, the tasks and the results pursued are similar. In Germany, the "Official Scale of Fees for Services by Architects and Engineers" (HOAI) includes nine service phases, which are listed on the left-hand side of Table 1. The first phase, called basic evaluation, includes the clarification of the task. This means, for example, the framework which has to be taken into account. In the second phase (Pre-planning), a space plan is created and the first drawings are proposed, among other things. In the third phase (Draft planning), the drawings are developed further in detail, including the technical equipment, and costs are calculated. After the preparation for the construction approval in the fifth phase, the planning procedure envisages the required steps for construction and the associated monitoring in the remaining steps. In contrast to this, the American Institute of Architects describes five phases called "Schematic Design", "Design Development", "Construction Document", "Bidding" and "Construction". Comparing both divisions of the planning procedure, the difference is discernible in different subdivisions. The description of the phases of both examples enables a sequential procedure and presents the achievements of each step. Each service phase describes the required planning tasks and the billable costs. However, the first phases of the HOAI, which are important for the building quality in particular, provide low financial compensation. This is one reason why it is controversial and much-discussed (Erdell, 2006).

Table 1. Comparison of the service phases of the Official Scale of Fees for Services by Architects and Engineers in Germany (HOAI §43, 2013) for civil engineering structures and the four phases of the product design process (VDI 2221)

Service phases in the building planning process	Phases of product design
1. Basic evaluation	Planning and task clarification
2. Pre-planning	Conceptual design
3. Draft planning	Embodiment design
4. Approval planning	
5. Execution planning	Detail design
6. Preparation of the contract awarding 7. Participating in the contract awarding process 8. Site management 9. Project supervision/support	

Based on the development of the construction industry, the current procedure is unsuitable and different approaches for new processes are suggested (Bergmann, 2013; Erdell, 2006). One option which is applied in the Netherlands and Great Britain in particular, is the so-called "construction team". It aims for closer networking between the planners involved and craftsmen as early as the first planning steps (Bergmann, 2013). Another example is the integrated project delivery (AIA, 2007), an extensive approach for optimising the existing process. Contractors, suppliers and facility managers are involved in this, as are the end users. Furthermore, the inclusion of the Building Information Modelling (BIM) is part of it. Using this tool, it is possible to create a three-dimensional model of the building to be planned. The model contains plenty of information and is made to support the cooperative development, access and the exchange of current planning results.

However, the current procedure and all of the presented proposals are not appropriate for planning and developing Adaptive Buildings. For more complex and interdisciplinary planning tasks, adapted processes are required more than ever. In the following section, this paper refers to the German procedure. Later, the targeted methodical support for planning and developing Adaptive Buildings has to be analysed in order to identify the demand for a change to a different processes.

4.2 Existing methodical support in mechanical engineering

In product development, holistic methods and processes are already established, e.g. (VDI 2221; VDI 2206; Pahl & Beitz, 2007). In these cases, the development process is divided into several phases such as "planning, conceptualising, drafting and elaborating" by Pahl & Beitz (2007) or as listed on the right-hand side of Table 1 by VDI 2221 (1987). Furthermore, most bigger companies with a development department as well as different trades work using customised procedures similar to the listed development processes, e.g. special adaptations for vehicle development. The processes are intended to provide a structured – and above all purposeful – procedure.

Besides these holistic processes, different methods are provided for each planning step. For example, function structures disassemble the developing problem systematically and design catalogues support the search for suitable working principles. Klein (2013) presents different construction methods such as integral or differential construction methods for lightweight design. Furthermore, a number of "Design for X" guidelines offers support when designing. Examples are "Design for ease of assembly" or "Design for recycling" (Pahl & Beitz, 2007). In addition, a lot of methods exist for independent use of special development phases. For this context, methods for evaluation (e.g. of different solutions), quality assurance, reliability and the safety concept are appreciable.

4.3 Adaptive Buildings

In the construction industry, three lightweight design strategies are already known which are, as already mentioned, also applied to mechanical and automotive engineering. In addition to material lightweight design (referring to the substitution of materials with a low density), structure and system lightweight design also exist (Sobek, 2007). Structure lightweight design targets a load transfer with low material usage while considering specified constraints. System lightweight design stands for functional integration, meaning that one construction element fulfils multiple functions. In addition to lightweight design strategies in building design, realised examples of manufacturing and conditional lightweight design can also be found. Compared with the lightweight strategies for product development presented by Henning (2011), the same lightweight approaches exist in the construction industry. The approach of the adaptability of buildings allows another lightweight concept to be realised which additionally reduces the mass requirement. This concept is explained in detail in the following section.

Irrespective of their field of application, conventional construction elements do not usually have varying physical characteristics such as breaking strength or stiffness. In the concept of a support structure with these construction elements, their stresses are connected with the most critical expected loading condition. The construction elements in question are usually appropriately dimensioned for this particular loading condition. Because the stresses only occur temporarily and the critical stresses may possibly never appear during the life cycle, the structure includes locations which are ineffective. (Sobek, 2007)

In order to improve the described state, structures could be designed to adapt to the loads acting on them with self-controlled processes. The adaptation should perform such that the stresses are as homogeneous as possible and that peak stresses are avoided (Sobek, 2007). By homogenising the stresses, the inherent weight of a construction can be reduced, and in places quite significantly. Additionally, oscillations caused by dynamic loads can be damped, too. Systems which change themselves aided by self-controlled or self-organised processes are called adaptive systems (Sobek, 2007). In order to realise an adaptive system, a high degree of system understanding, sensors, actuators and real-time control are required.

As already stated in the introduction, the potential of adaptive systems in buildings is seen in the actuation of the support structure of buildings and the building envelope. Whereas the adaptability could be used as described in adaptive support structures to increase their loading capacity and to realise lightweight design, facade elements are also able to interact with the environment. Conventional parts of the building envelope are equally non-varying. The permeability to air, temperature, sunlight etc., for example, can be influenced. By using the adaptiveness, facade elements can be designed to store energy using their layers to store heat radiated by the sun. Later, the elements emit the heat into the building. A building which has an adaptive structure or an adaptive envelope is called an Adaptive Building.

In the following section, three results of a literature research about adaptive elements and structures are briefly presented. They are the most complex examples which aim primarily the mass reduction of the respective building. Figure 1 shows an example of an adaptive facade element. A pneumatically switchable opening facade element allows the exchange of air through the inside of the envelope. A heat-storing and insulating layer is installed in it (Haase, 2011). Figure 1 shows the facade element with an opened surface layer on the left-hand side and with a closed surface layer on the right-hand side.

Figure 1. Example of adaptive facade elements (Haase, 2011)

Alongside this adaptive element for the building envelope, approaches for adaptive structures exist, too. Neuhäuser (2014) developed the Stuttgart SmartShell, which is an adaptive shell structure with a span of 10 m and a thickness of 4 cm. By using shell structures, it is possible to bridge wide spans with a minimal weight. This is due to the fact that in the ideal scenario, the double-curved form allows the load transfer as a pure compressive stress to avoid bending stresses. Figure 2 shows the simulated equivalent stress of the passive and adaptive state of the shell. To reduce the visible peak stresses caused by external loads, for example wind or snow, three of four bearings are actuated using hydraulic cylinders. Furthermore, the actuators also damp oscillations. Thus it is possible to reduce the thickness and the weight to a minimum size and to optimise the relationship of payload and inherent weight (Neuhäuser, 2014). For planning and developing the Stuttgart SmartShell, knowledge about the integration of the actuators into the structure, its bearings as well as the control concept with the damping was required alongside the form-finding.

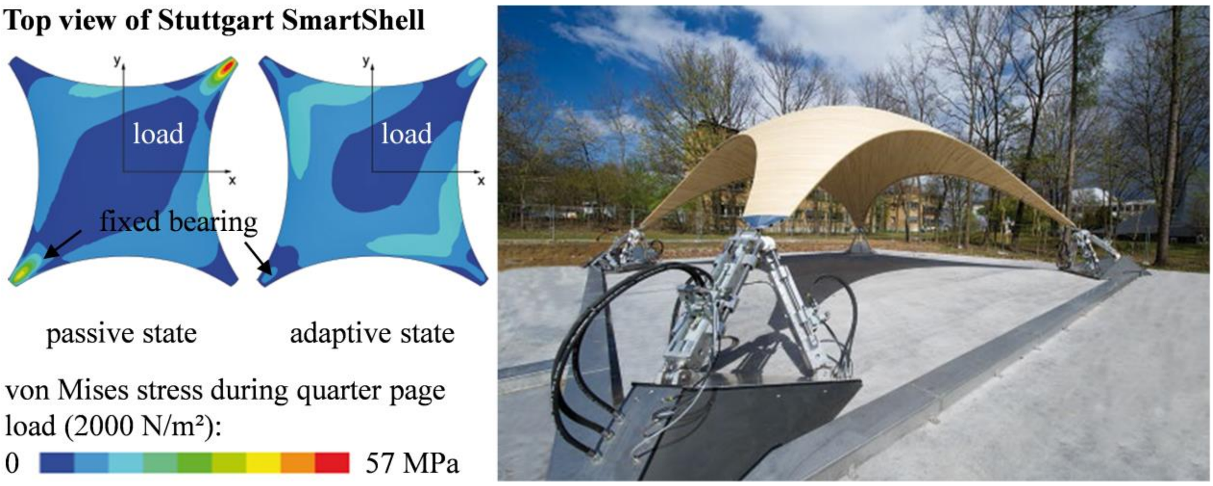

Figure 2. Adaptive structure Stuttgart SmartShell (Neuhäuser, 2014; Bosch Rexroth)

Another approach for reducing the material requirements with the adaptability of a construction is shown by the idea of the "Stuttgarter Träger" (Teuffel, 2004). The study is based on a single-span girder with a considerable ratio between construction height and a span of approximately 1/500. By shifting a horizontal movable support, deformations which are a result of crossing loads could be avoided. The functionality and the lightweight potential have been proven with a model (Teuffel, 2004).

For adaptive structures, it was demonstrated that more energy can be saved than is needed for actuating (Teuffel, 2004). It is conceivable that the energy balance of an Adaptive Building using adaptive facades as well is even better still. However, it is clear that the whole planning and developing process for buildings with such adaptive elements is significantly more complex and challenging than for conventional ones. The following investigations are based on these examples of adaptive elements and structures.

5 Comparison of basic aspects of civil engineering and product development

To answer the question what challenges and what demand for a methodical support for the planning of Adaptive Buildings exist, this paper compares differences between the construction industry and mechanical engineering first. Figure 3 shows the basic differences, which are derived from a comparison of the life cycle of a building and a technical product. It is noted that these differences apply to normal-use cases. For example, prefabricated houses or special-purpose machinery and auxiliary tools are excluded. However, based on the identified basic differences of the comparison the plant engineering can be classified between building industry and mechanical engineering.

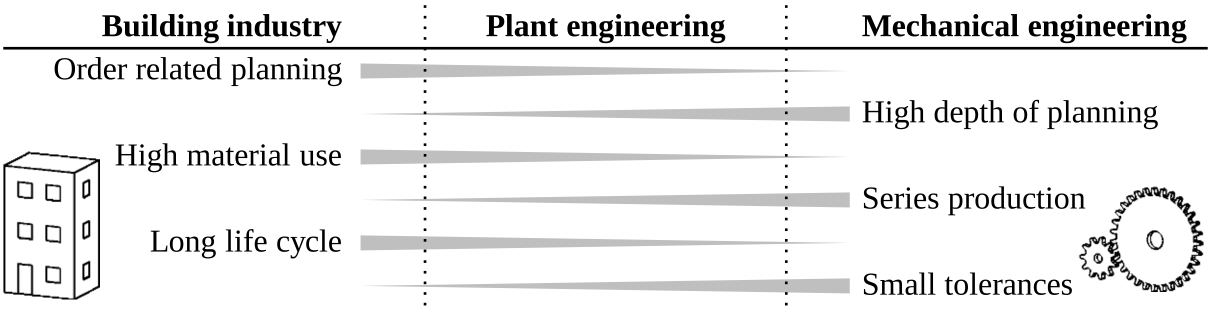

Figure 3. Basic differences between the construction industry and mechanical engineering (in general)

In contrast to the order-related planning in the construction industry started by the building owner, the development of products starts within a company. Due to different regional requirements, each building is individually planned and implemented. Contrary to this, the aim in mechanical engineering is to divide the development costs between a high number of pieces through series production. However, these costs might be higher because of the required depth of planning (Lindemann, 2005). Each piece, independent of its size, is fully described when it is handed over to production. This description of the dimensions, the surfaces etc. is subsequently reviewed during manufacture to make sure if the small tolerances are implemented. It is obvious that buildings incur immense material requirements and are built for a period as long as possible. Whereas technical products are typically designed for some years, for example a concrete mixer with a maximum life cycle of 20 years (Ehrlenspiel, 2013), the life of a building is typically 80 to 100 years – and even longer with modernisations.

These described main differences have to be considered while researching a holistic planning process. Within the scope of Adaptive Buildings, the contrasts will adjust. In order to reduce the material usage, the planning depth will be increased, caused by a rising number of calculations, models, simulations etc. The requirement for smaller tolerances will increase, too. It has to be analysed to what extent a common-part strategy is possible with regard to Adaptive Buildings. Despite these basic differences, the application of methods which are known in product development is generally possible in building planning (Lindemann, 2005) and therefore also in common usage.

Comparing the first steps of the planning process of buildings with the product development process provides the result that they are – in principle – similar (see Table 1). Both start with an analysing step and increase the level of detail. The basic evaluation of the planning process targets the same purpose (clarification of the tasks) as the planning phase in mechanical engineering. The following steps of both processes provide the conceptualisation including drawings and estimations, which have to be concretised afterwards in detail. In contrast to mechanical engineering, the planning process of buildings also contains the monitoring of the construction work in the following steps. Whereas the process of product development in mechanical engineering guides the users until the preparation for production, the planning process of the construction industry ends with the handover of the building to the owner. Another peculiarity and fixed component of the planning process concerns the approval planning required in order to achieve construction approval. For this paper, it is also important that the number of established methods, methodical tools and so on is lower in building engineering than in mechanical engineering; both recommended in planning processes and in practice. For this reason, some approaches address the transfer of methods from mechanical engineering to the application in civil engineering (Lindemann, 2005; Schmid, 2015). However, these methods are not transferred or developed further for application in connection with Adaptive Buildings.

6 Challenges and the demand for methodical support for a holistic planning process

With the cooperation of mechanical engineering, electrical engineering and computer engineering in mechatronics, technical systems developed in a great dimension. To this end, new procedures, processes and coordination between the disciplines were required and developed, amongst other things. With the comparable cooperation of architects, civil engineers and engineers from the field of mechatronics to realise Adaptive Buildings, a similar initial situation exists. It is obvious that the goal is not attainable without the described composition of associated technical knowledge.

To develop an extended holistic methodical support for the planning of Adaptive Buildings, aspects to be considered must first be identified. After analysing the described initial situation, the aspects identified were contrasted and compared with the goals of design methodologies presented in Ehrlenspiel (2013) and Pahl & Beitz (2007). The results can be summarised in four main challenges while planning and developing Adaptive Buildings. To demonstrate the demand for support, requirements are derived for each challenge. These requirements are assigned to the four main challenges in Table 2. Furthermore, the planning period should not increase dramatically. Therefore, the methodical support has to be analysed with regard to which tasks and which results may be planned simultaneously. However, there are several well-known approaches in mechanical engineering.

Table 2. Main challenges in the development of a holistic methodical support framework for planning and developing Adaptive Buildings with derived requirements

<table>
<tr><td rowspan="6">Challenge 1</td><td>New level of cooperation between the disciplines involved in the building planning process to solve a complex problem</td></tr>
<tr><td>The knowledge and competences of the different disciplines have to be shared and matched, and interfaces have to be defined.</td></tr>
<tr><td>Clear allocations have to be determined.</td></tr>
<tr><td>The individual planning task of the specific building has to be simplified, for example by dividing the task into simpler ones with a recommended solution strategy.</td></tr>
<tr><td>The structured procedure has to promote purposeful planning to decrease the planning effort.</td></tr>
<tr><td>The procedure should be adaptable to technical advances in the future.</td></tr>
<tr><td rowspan="6">Challenge 2</td><td>Large number of decisions while planning and developing</td></tr>
<tr><td>The methods should support the planners and developers involved during each step of their decision-making, especially if they could be described as skill-intensive, complex, error-prone, relevant to security etc.</td></tr>
<tr><td>Reproducible and comprehensible results are requested, for example by using evaluation methods to analyse different solutions.</td></tr>
<tr><td>The process has to envisage expected results to achieve completeness.</td></tr>
<tr><td>If possible, appearing options should be envisaged and described in sufficient detail.</td></tr>
<tr><td>Finally, decisions with important cost impacts have to be supported and based on a selection of options.</td></tr>
<tr><td rowspan="4">Challenge 3</td><td>High number of requirements according to the safety and quality of the building</td></tr>
<tr><td>Security and quality requirements should be integrated into the planning procedure to achieve a secure technical system with a long life cycle.</td></tr>
<tr><td>Individual planning does not enable prototypes and adjustments are only possible within a limited framework. Therefore, intermediate reviews of the interim results are required and could lead to a continuously iterative procedure.</td></tr>
<tr><td>The support should refer to additional requirements like aspects of sustainability, resource efficiency and lightweight design, lower energy consumption and consequently low CO_2 emissions.</td></tr>
<tr><td rowspan="3">Challenge 4</td><td>Rare application of methods in the construction industry so far</td></tr>
<tr><td>Users of the planning team have to be quickly convinced by the (described) advantages of a methodical procedure.</td></tr>
<tr><td>The methodical support should provide support without a time-consuming teach-in process before application.</td></tr>
</table>

Of course, each methodical tool which should form a part of the holistic support framework has to fulfil specific requirements which are not covered in the given overview. For example, Keller (2009) presents detailed groups of requirements with respective items (e.g. usefulness, comprehensibility, flexibility etc.) which apply in order to develop such tools in their universal validity.

7 Conclusion and outlook

The planning and development of Adaptive Buildings is a versatile task. The paper demonstrates this fact using different examples of adaptive elements and structures. The analysed differences between mechanical engineering and the construction industry in terms of technical boundary conditions, the listed challenges and derived requirements as well as the respective methodical procedure are the basis for the further development of methodical support to plan more complex buildings. The latter have to be validated during the next research step.

The field of mechanical engineering and the construction industry have introduced the integral planning approach (Ehrlenspiel, 2013; Bergmann, 2013; Erdell, 2006), which is based on an early inclusion of all members involved in the respective planning development team. Against the background that complex tasks should be solved in a collaborative manner, this planning approach is seen as a suitable basis for holistic support. In the further research steps, the interactions between the team members and their results have to be analysed.

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