Individualized standardization as the overarching principle in the context of planetary boundaries

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Abstract. To drive forward a fundamental change in the construction sector to achieve environmentally friendly progress in the construction processes, one promising approach is the synchronous implementation of the three main drivers technology, construction, and design. The key to this transformation is end-to-end digitalization. Our approach aims to achieve a new architectural quality by linking digitized design tools, ecological and environmentally friendly concepts, and serial production processes. Against this background, two research projects were advanced to enable adaptive prefabricated systems based on combined additive manufacturing. Two case studies illustrate the research results. In the first, a digital assessment tool is being developed to improve planning processes. With the tool, standardized yet adaptive constructions can be evaluated according to their sustainability impact in an early design phase. The second approach focuses on delivering a customized material composition realized with additive manufacturing methods. In an automated co-extrusion process, the dimensions and building physical quality of story-high wall panels (floor-to-ceiling) can be adapted to individual requirements. The optimum balance of standardization vs individualized building solutions will introduce a novel flexibility for the architectural design process as well as a higher production efficiency. This strategy of individualized standardization is based on integrative collaboration and visionary research.

Keywords: Individualized standardization, case study, lightweight aerogel concrete technology, adaptability, sustainability assessment

1. Relevance

1.1. Delimitation of the construction sector

Traditional processes, vast complexity, and high carbon dioxide emissions describe the serious difficulties the building and construction sector faces today. In addition, the continuous shortage of housing over the past decades has gained further relevance and has become a driver in socio-cultural, political as well as economic terms. According to the German federal statistical office (Destatis), the increase of the German population by 2.5 million people (+ 3.1%) between 2012 and 2018 indicates that a related increase in housing or residential buildings, among other factors, will continue. According to
this expected further increase in housing demand, the German government declared its goal to build about 1.5 million apartments in the following years as part of the Housing Summit in September 2018. A big stumbling block hindering the achievement of this goal is the fact that the productivity contribution of digitization measures in the German construction industry has been rather low so far. [1] Topics such as ‘Trends on Construction in the Post-digital Era’ indicate a turning point. However, the question arises whether we have actually arrived in the post-digital era, as digitization has not yet been successfully combined or implemented in the construction sector in a manner that can respond to the growing demand for increased productivity.

According to Glock, in the past, the focus lay on optimizing various individual research fields in the area of design and construction. But the view of the entire value chain, as well as user needs, was neglected. [2] It must be noted that digitization has indeed arrived in subsectors and individual processes of the construction industry; however, the overarching implementation of integral planning has not yet taken place.

1.2. Lack of a continuous digitalization strategy
The challenges arising from this transformation clearly require an overarching principle. For an ongoing and long-term digitalization strategy, it is crucial to focus on circularity (circular economy) across the entire resource management and accompanying processes. Sustainable and ecologically oriented construction sector development requires a holistic approach to planning and production. The correlation between material composition, material production, construction method, end-of-life scenarios, and building operation is the key to a circular planning process.

Currently, there is no digital tool to assess different construction methods in connection with sustainability potentials that the planner can use as early as in the design stage in phase 0. [3] Furthermore, no sustainability improvement strategy is available that continuously transfers the design data into execution and beyond. Tools for sustainable planning are needed to further develop and link planning methodology and process quality.

2. Objective: Synchronous implementation of the three main drivers technology, construction, and design and transition to a circular economy
Scientific research confirms the advantages of continuous planning processes based on the implementation of systemization methods while simultaneously providing diversity in architectural design. [4] The synchronous implementation of the three main drivers ‘automated production, systematized construction, and digital design’ is considered highly promising to bring about a substantial shift that will lead to planetary friendly progress of construction processes.

![Figure 1. Integral planning approach based on material technology, architecture and construction method, and production process.](image)

The parameters ‘technology’ and ‘construction’ provide the potential to improve construction methods by implementing automated prefabrication technologies and intelligent components. The third parameter ‘design’, namely design variance, is essential to achieve broad acceptance of the architecture developed based on the first two parameters.
By merging systematization strategies and specific adaptability of building components, a new variance can be realized that also incorporates efficiency aspects. This is only possible by employing production automation and process digitalization simultaneously, which will have a significant impact on sustainability aspects.

Achieving sustainability requires a very differentiated view that is not limited to individual, absolute inputs in the life cycle assessment but, again, asks for optimization of all three parameters technology, construction and design. For example, adaptation strategies to climate change must take into account much more than just optimizations at material level. One goal is undoubtedly to advance lightweight construction methods as far as possible because they minimize the use of resources and CO₂ emissions in various ways. But at the same time, it is important to continue future-oriented development of the primarily used construction methods of timber, steel and solid constructions rather than favoring only one construction typology. Particularly regarding a conscious use of resources and necessary adaptation strategies in the building industry, target-oriented development must include a differentiated evaluation and optimal combination of hybrid construction methods. Rethinking must occur as early as in the beginning of a project, during the design and tendering phase, if a circular economy is to be achieved and sustainable effects are to be developed in practice.

The thesis of individualized standardization as an overarching principle can be proven with two case studies that represent the focus of this research. As described in the following, the selected case studies deal with different construction methods and material technologies, but, in their difference, together they serve as evidence of the benefits of a synchronous implementation strategy and provide a solution towards a circular construction industry. They emphasize that the simultaneous application of the three main drivers technology, construction, and design offers transfer potential for a variety of other research activities.

3. **Case study 1: Research into adaptable systems**
The research is conducted as a collaboration between the Juniorprofessorship of Resource Efficient Building Constructions of TU Dortmund, Design-to-Production GmbH in their role as experts of digital planning and production methods, and industry partner Solid.box GmbH who is specialized in precast modular (building) constructions. The targeted research focuses on the development (planning and production) of prefabricated components in hybrid constructions. Continuous digital planning and production processes will result in higher constructive flexibility and design variance, thus contributing to the improvement of sustainability for the building sector.

3.1. **Interface between systematized construction and digital design**
The introduction of serial processes determines the production of buildings, especially in residential construction. In order to challenge current concepts, planning methods must adapt to a new way of constructing buildings. In addition to offering economic advantages, they have to simultaneously focus on improving sustainability factors.
Standardization, so far, is mainly applied to material classifications and construction methods. In the building sector, hybrid constructions and components are common. In prefabrication, however, the idea of a hybrid factory rarely exists. As a result, sustainability potentials with regards to 1. saving resources and 2. extending the potential of circularity from planning to deconstruction remain unexploited. The opposing factors of variance and efficiency are directly related to the size of components or modules and their geometry. In this context, the use of modular structures is characterized by extremely systematized planning methods, very efficient production processes in the factory, and on-site assembly. Regarding the degree of automation, a large share of the execution work generally still takes place manually. [5]

Even in the factories, there is a lack of automated processes. Meaning that factory-based fabrication still mainly depends on traditional labor. While the used methods maximize synergies and thus profitability, the processes lack flexibility and independence from human resources. Only an interlocking strategy can overcome the existing limitations previously described.

3.2. Digital sustainability assessment
A study by Fraunhofer IAO on the topic of “Digital Planning and Manufacturing Methods” shows that there is still an enormous interface problem between the partners involved in planning, execution, and manufacturing. [6] Closing this gap should enable more efficient processes while at the same time providing a high degree of design flexibility in architecture and construction. To improve sustainability, the increased use of modular, systematized building designs can only be successfully pursued if the system is available at the user level and tangible on the market. In this way, the cycle can be closed from the initial design concept, which is currently not yet fully implemented, to automated production and recycling.

With the development of a planning tool, the research project aims to facilitate a multi-layered circular economy. According to Helmus, currently available planning tools do not yet sufficiently incorporate the optimization of material cycles through BIM. [7] And no planning tool exists that enables an evaluation of building structures with regard to sustainability aspects in the design phase. The research objective is to transfer the necessary parameters of a construction task into a holistic planning process and ultimately make them accessible to the planner. In this context, target-oriented development means the development of a digital design tool that evaluates the footprint from the very beginning of a project to map the entire process from the early phase of architectural design planning to (partially) automated production. The information model under investigation is no longer a rigid system that has
to be fed at the beginning of a (design) process but rather a system that allows for continuous growth, adaption, and follow-up cycles at any time through digital associations.

There is great potential to integrate re- and up-cycling platforms such as Madaster. After developing a database for prefabricated construction methods, it is necessary to create an interface to existing material registers. End-to-end process linkage and access to existing material cadasters (registers) will be complemented by improved digital sustainability.

3.3. Hybrid kit-of-parts construction

Based on an adaptive-associative building system, this planning approach systematically combines three-dimensional room modules consisting of an outer shell, a panel, and linear elements. These components, brought together in an automated production line, can be used to create various solutions for multistory building typologies.

The uniqueness of the research approach lies in the complementary combination of prefabricated room modules and panel components in one construction process. This approach allows for an adaptive construction method that meets the complex requirements of today’s planning tasks by offering a high degree of flexibility in terms of both material construction and design variance.

The kit-of-parts approach differs significantly from the current state of the art, with its system openness being the most important factor. It is implemented by developing a novel digital design tool that generates a configuration based on serial manufacturing methods in the form of a system-based design platform in hybrid construction. As a design and evaluation tool, it represents an extension of the techniques currently available on the market. According to our research results, promising effects can be achieved especially in serial, but partly adaptive construction. With its modular principle of a uniform design methodology, it should be possible to react adaptably to different individual requirements through automated hybrid manufacturing.

Furthermore, hybrid construction methods from multiple manufacturers are to be successively incorporated. In this way, the concept will promote a new way of thinking among planners and will also get manufacturers on board.

**Figure 3.** Linking of research parameters with transfer to the respective fields of work.
4. Case Study 2: Intermediate strategy between systematization and individualized construction

This research was a collaboration between the TU Dortmund professorships 1. chair of Building Construction (Piet and Wim Eckert) and 2. Juniorprofessorship of Resource Efficient Building Constructions (Jutta Albus) and the industry partner G.tecz Engineering GmbH, a concrete specialist with material composition and production expertise. The resulting development ties three significant drivers and frames the research achievement on the triad of production, construction, and digital design.

4.1. Material technology and automated production

Increasing digitization in the construction industry through automation and robotics is changing the approach to materials and their interconnection. Claypool, Jimenez Garcia, Retsin, and Soler state the potential of 3-D printing in view of combining different functions within one system. [8] Automation processes allow materials to be used more precisely and thereby actively conserve resources. In the construction industry, the application of conventional processes and the use of pre-dimensioned building products often lead to oversized components and, thus, excessive material use. In contrast, the previously described approach of combining processes and parameters enables the generation of functionally optimized components. This term refers to the relationship between material properties and material consumption. Consequently, resources are used only where they are absolutely necessary. The advantages of functionally optimized constructions have been proven by research at ILEK in Stuttgart amongst others. [9] Concrete is particularly suitable for the required automated manufacturing processes due to its liquid consistency before hardening (plastic state). Its adaptability and flexibility in modeling increase the design quality. The interdisciplinary DFG research program “SPP 2187 Adaptive Modulbauweisen mit Fließfertigungsmethoden” examines the development of partially adaptive modules, which are integrated into an automated flow production process.

In addition to processability, constructions based on a mono-material matrix offer great potential regarding sustainability as well as recyclability. Material compositions with improved heat-transmission properties eliminate the need for additional insulation, and some even have structural properties. The advantages of monolithic wall structures on the constructive, economic as well as ecological levels are manifold and have been examined by Tersluisen et al. [10]

Currently, material innovation and automated production processes are rarely optimized in parallel. The use of 3D concrete printing focuses on the technology and the degree of automation but largely ignores the perspective of material improvement. Insulating concrete, for example, is often produced traditionally and in situ and is rarely used in prefabricated form. Additive manufacturing technologies rarely implement insulating concretes; until now, they have only been explored in a few isolated cases, as demonstrated by the CONPrint3D-Ultralight® research at TU Dresden. [11]

Our investigation, as described in the following, should be seen against this background. For the conducted aerogel research project, an optimized machine technology was developed in synchrony with the isolating material matrix, which is highly suitable for additive manufacturing.

4.2. Function-optimized components

Our research has provided evidence that the innovative liquid concrete mixture with insulating function can be successfully used in an automated production process. An adaptive building system was developed for standardized wall, ceiling, and floor panels based on these results. The system allows to change the module dimensions according to its application-specific functions and thus respond to the individual requirements of a construction task through adapted material compositions. Integrating the novel concrete material into an automated continuous manufacturing process made it possible to produce a component consisting of two nano-optimized UHPC face layers and a highly insulating, load-bearing lightweight concrete core. The aerolightweight concrete enables intelligent detailing and prevents the formation of thermal bridges due to its homogeneous insulation effect across the entire element section of 36 cm. The advanced mono-material thus meets the current European regulation standards for insulated wall constructions.
Due to the foamed concrete’s lower density, porous lightweight aerogel concrete requires 50-70% less cement per m³ compared to concretes of classes C25/C55, which are generally used in building constructions. For a comparison of the two materials, we need to consider that a lightweight aerogel concrete wall structure is assumed to have a cross-section of 36 cm, while a wall structure made of standard C55 concrete is assumed to have a cross-section of 15 cm. In spite of the greater thickness of the lightweight aerogel concrete wall, this results in a 30-50% cement savings potential per square meter wall area compared to standard concrete, with the additional benefit that the cement-reduced version provides insulation whereas the standard concrete wall requires an additional insulating layer. Against this background, the decarbonization of the construction industry can be advanced through a conscious reduction in the mass of raw materials used and their intelligent application with regard to new materials and manufacturing technologies. The optimal lightweight aerogel concrete matrix, which consists of UHPC, foam concrete, aerogel, and lightweight aggregate, has the following properties:

| properties                        | values                   |
|-----------------------------------|--------------------------|
| density                           | 550 kg/m³                |
| compressive strength              | 1.75 N/mm²               |
| (after 7 days)                    |                          |
| rapid concrete*)                  | 0.67 N/mm²               |
| (after 15 minutes)                |                          |
| rapid concrete*)                  | 1 N/mm²                  |
| (after 60 minutes)                |                          |
| thermal conductivity              | 0.088 W/mK               |

*) Based on a different raw material selection and aerolightweight concrete recipe.

Figure 4. Mobile machine equipment showing the assembly belt production © G.tecz Engineering GmbH
5. **Research conclusion and outlook**

Research in building construction has brought about a variety of approaches that foster the improvement of sustainability measures and solutions that incorporate circular processes. However, the decisive factor is not the circularity of a single parameter per se, such as the material or the construction method. The solution lies in linking and integrally implementing the triad of technology, systematization, and design. This approach is central to improving sustainability.

By synchronously optimizing these three guiding factors in the development process of the aero lightweight technology, a sustainable product can be realized taking into account the entire life cycle. Compared to the mentioned research results, the developed technology incorporates the previously criticized aspects within one product. For the first time, an insulating lightweight aerated concrete is created in an automated production process, featuring functional layering (water-repellent UHPC face layers and highly insulating foamed concrete core), thus offering the targeted use of materials. This approach has great potential for transfer sustainable building systems. The load-bearing and insulating wall panels presented in Case 2 differ from existing solid wall constructions in their material composition due to the significantly reduced use of starting materials (reduction of the cement content and substitution using RC components). A comparative life cycle assessment was carried out with a solid (single-shell) aerated concrete wall construction and a classic external thermal insulation composite system. Furthermore, the surface-finished wall system is based on a high degree of prefabrication while allowing for project-specific adaptation, made possible by the faster-hardening concrete as well as the automated production technology. Another factor to consider is that production in a local production unit reduces a large part of the emissions caused by the transport of both the raw materials to the plant and the materials to the construction site and forces a local use of resources, which becomes particularly relevant with regard to the use of RC components. Synchronous improvement on multiple levels, such as raw material use, emission input, production, transport, maintenance, recycling, etc. and optimization on the process level, which is essentially not depicted in the LCA, make possible respectful handling of the planetary boundaries.

Robotization as a multiple manufacturing technology can enable these parameters in one cycle. The crucial transfer from research to a continuous design workflow could be installed with the new
technology. Thus, the entire process chain can be mapped, from concept planning to design and joining principles to manufacturing and assembly. With regard to manufacturing, two aspects are crucial. First, it is not expedient to solve a complex construction task with just one overarching technology, such as 3D printing a complete house. Rather, maximum efficiency can be achieved by bringing together multiple manufacturing technologies. In that regard, a hybrid factory setting mentioned in the first case study is critical. Robotization in this context is one way to synergize different processes and trades. Second, it is important to ensure that scientific innovations are successfully implemented in the construction industry.

As demonstrated in Case 1, the existing gap between planning and production can be successfully closed with the developed digital tool. This new digital sustainability assessment subsequently leads to more efficient construction methods. For example, construction and joining techniques can be adapted in terms of the processes employed. Materials can be used in a more targeted manner and can be optimized in terms of function. This leads to a notable improvement in resource efficiency right from the start of a planning process and reduces complexity.

Based on both case study research results and considering individualized standardization as the overarching principle, an optimal balance between standardization and individualized building solutions leads to novel flexibility in the architectural design process. Thus, higher production efficiency can be realized through automated production and digitalized planning processes, contributing to resource-saving and efficient construction strategies. The combined approach leads to project-specific adaptability, proven in two different ways. This refers to the ability to modify a design principle or a production process so that the entire system itself remains the same, but dimensions or layers of components can be scaled or material compositions adjusted. The result is adaptive systems growing with their functions to meet application-specific requirements.

This strategy of customized standardization is based on integrative collaboration and visionary research. Architects as incubators manage this socio-cultural, economic, and ecological challenge with a holistic approach that opens up new fields of action by starting with small scale solutions and translating them into global accelerators.

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