Received: 29 April 2021 | Accepted: 2 June 2021

DOI: 10.1002/cend.202100019

FULL PAPER

Ernst & Sohn
A Wiley Brand

Industrializing precast productions

Adaptive modularized constructions made in a flux

Peter Mark[1] | **Gisela Lanza**[2] | **Daniel Lordick**[3] | **Albert Albers**[4] | **Markus König**[5] | **Andre Borrmann**[6] | **Lothar Stempniewski**[7] | **Patrick Forman**[1] | **Alex Maximilian Frey**[2] | **Robert Renz**[4] | **Agemar Manny**[7] | **Jan Stindt**[1]

[1]Fakultät für Bau- und Umweltingenieurwissenschaften, Lehrstuhl für Massivbau, Ruhr-Universität Bochum, Bochum, Germany

[2]wbk Institut für Produktionstechnik, Karlsruher Institut für Technologie, Karlsruhe, Germany

[3]Institut für Geometrie, AG Geometrische Modellierung und Visualisierung, Technische Universität Dresden, Dresden, Germany

[4]IPEK – Institut für Produktentwicklung, Karlsruher Institut für Technologie, Karlsruhe, Germany

[5]Fakultät für Bau- und Umweltingenieurwissenschaften, Lehrstuhl für Bauinformatik, Ruhr-Universität Bochum, Bochum, Germany

[6]Lehrstuhl für Computergestützte Modellierung und Simulation, Technische Universität München, Munich, Germany

[7]Institut für Massivbau und Baustofftechnologie (IMB) – Abteilung Massivbau, Karlsruher Institut für Technologie, Karlsruhe, Germany

Correspondence
Patrick Forman, Ruhr-Universität Bochum, Fakultät für Bau- und Umweltingenieurwissenschaften, Lehrstuhl für Massivbau, Bochum, Germany.
Email: patrick.forman@ruhr-uni-bochum.de

Abstract

Building in heavy rain is seldom beneficial, but common practice on site. It promotes inaccuracies and impairs the use of modern but sensible high-performance materials and costs time, since disruption in construction frequently causes complicated returns to the planning process. Nevertheless, a handcrafted production process is still considered the one and only alternative since all buildings are unique and thus must be manually constructed on site. Indeed? The priority program entitled "Adaptive modularized constructions made in a flux" funded by the German Research Foundation follows a completely new approach. Buildings are divided into similar modular precast concrete elements, prefabricated in flow production, quality-assured, and just-in-time assembled on site. Comparable to puzzles with many pieces, the uniqueness of the structure is maintained. The motto is: "Individuality on a large scale-similarity on a small scale". The contribution presents approaches of modularization, production concepts, and linking digital models. Serial, stationary prefabrication enables short production times and resource-efficient modules that are assembled to load-bearing structures with low geometrical deviations. Stringent digitalization ensures high quality of all intermediate steps. These comprise fabrication, assembly, and the whole service life of the structure. The result is a lean production process.

KEYWORDS

building information modeling, construction kit, digital twin, flow production, industry 4.0, modular construction, modularization, precast concrete members, quality management

1 | INTRODUCTION

Construction activities dominate the worldwide energy consumption with about 40% - and the tendency is increasing.[1] The main reasons for this are the rising living standard of people, unbroken population growth, and the scheduled replacement of buildings after their use.[2,3]

According to the central forecast of the United Nations,[4] the world population will increase by another 2 billion people in the next 25 years. This increase is almost equal to the number of people who lived on earth in 1930. In just 25 years, additional buildings and infrastructure will have to be constructed that corresponds to that of 1930—not including increases in living standards.

The demand for housing, infrastructure, and utilities is enormous, the associated global warming potential (GWP) gigantic. Concrete structures, therefore, play a decisive role. Concrete has established itself as the undisputed most widely used building material due to its

This is an open access article under the terms of the Creative Commons Attribution License, which permits use, distribution and reproduction in any medium, provided the original work is properly cited.
© 2021 The Authors. Ernst & Sohn Verlag für Architektur und technische Wissenschaften GmbH & Co. KG, Berlin

FIGURE 1 Team members and collaborating universities (photo: Julia Lippmann, graphic: Patrick Forman)

free shapeability, worldwide availability, and low material costs. The amount of concrete used each year adds up to almost four tons per person. The associated GWP is correspondingly high. The production of the basic material cement alone is responsible for ~5% to 10% of the worldwide CO_2 and is thus the highest single emitter.[2,5,6] The natural resources for concrete, such as sand or water, are becoming short.[5]

Europe's challenge is the replacement of constructions.[3] After the building boom in the 1960s to 1980s, schools, bridges, and industrial plants are now to be replaced by new ones. Their service life is simply over. However, it is not only motorists at the countless (permanent) construction sites who realize every day that slow building activities cannot be reconciled with our sensitively networked flows of goods and traffic. The replacement of constructions is stalling. The "arteries" of our industrial base are clogged up. Time and human labor are wasted, and the environment is polluted.

Here, the research concept of the priority program starts from Reference 7. The aim is to consistently minimize waste (lean production[8]) while maintaining individual, durable, and esthetic building structures. The aim is to use significantly less material, avoid errors, introduce consistent prefabrication with quality assurance, and thus achieve the fastest possible construction activity on site. The key is to break down concrete structures into similar individual modules which are mass-produced in a digitized production facility.

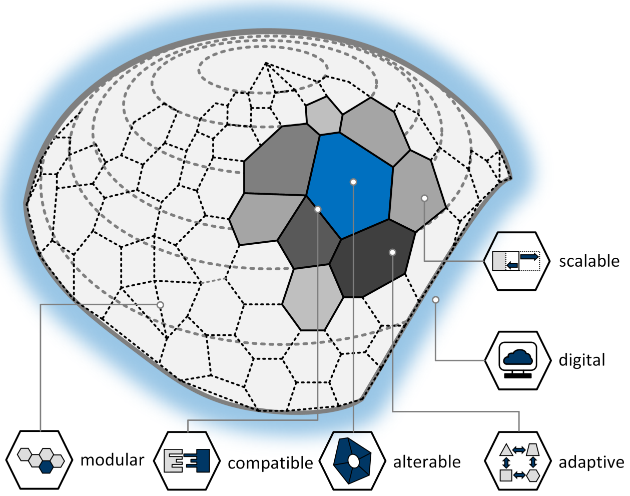

FIGURE 2 Segmentation of a shell into scalable modules along with characteristics for fabrication, assembly, and use (graphic: Patrick Forman)

2 | THE PRIORITY PROGRAM 2187 "ADAPTIVE MODULARIZED CONSTRUCTIONS"

The program "Adaptive modularized constructions made in a flux" (SPP 2187) was established in 2020 by the German Research Foundation (DFG). It is interdisciplinary and fundamental-oriented. Around 50 researchers from institutes of structural engineering, mechanical engineering, computation in engineering, and mathematics are working together to build as quickly and precisely as possible on-site using stationary serial prefabrication. Figure 1 shows the research team on the left in February 2020 and on the right the seven participating universities across Germany.

The possibility of serial production arises from the segmentation of load-bearing structures into modules, which can be plane or truss-like components. Figure 2 illustrates the basic principle using the example of a shell. The segmentation is not motivated by statical systems, for example, like modules of columns, beams, or plates, since

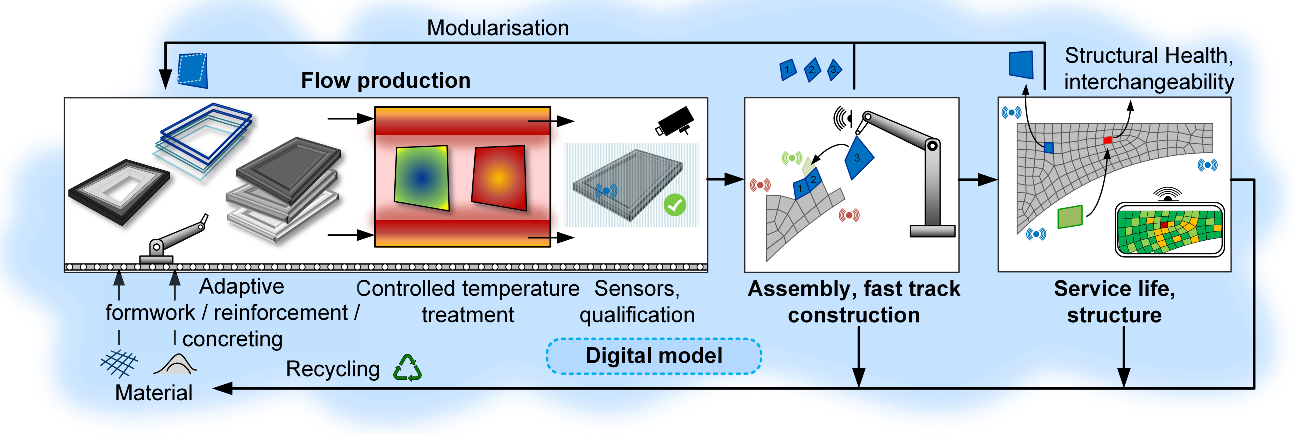

FIGURE 3 Robot-assisted flow production of concrete modules with rapid assembly using sensors and continuous digital modeling as well as quality control (graphic: Patrick Forman)

this hardly leads to a significant degree of repetition, but rather too extensive individual production (manufacturing) and high weights. Besides, complicated nodes are created. Instead, the manufacturing and joining process controls the pitch with the goal of high quantities and simple connections that are tolerable to errors. The modules are similar—not the same—and scalable in basic sizes. Scaling means that side dimensions, thicknesses, reinforcement quantities, or materials of the modules remain changeable (adaptive). The individuality of the overall structure is preserved like a mosaic or a puzzle with hundreds of individual pieces. A positive side effect of the modular concept is that modules can be exchanged during use (alterable), that is, the supporting structures can be locally repaired, reinforced, or adapted to changed utilization.

Stationary prefabrication eliminates the unavoidable inaccuracy of the construction site in favor of the quality of industrial flow production, as known from the automotive industry. Production speed, geometric and material precision, durability, and resource conservation through component optimization[9–11] are improved multiple times.

The modularization starts retrospectively from the bearing structure. The production of the modules in the factory and the rapid assembly yield the design of the modules. The rule is: process controls design – and not vice versa. Figure 3 shows this at the top. Production is automated in a linear flow principle (left side) with the individual steps of formwork, reinforcement, controlled temperature treatment for hardening,[12] qualification of the individual modules, and sensor-based labeling. The sensors are used for seamless tracking, assembly controlled by a digital twin (center right), and as indicators for assessing the load-bearing capacity or serviceability properties of modules[11] over their service life (right). A digital model controls all processes and interactions. In doing so, each module "knows" its properties (e.g., strength, geometry, position within the structure) and monitors them over their service life. Production can thus take place *just-in-time* without the need for additional storage space on the construction site.

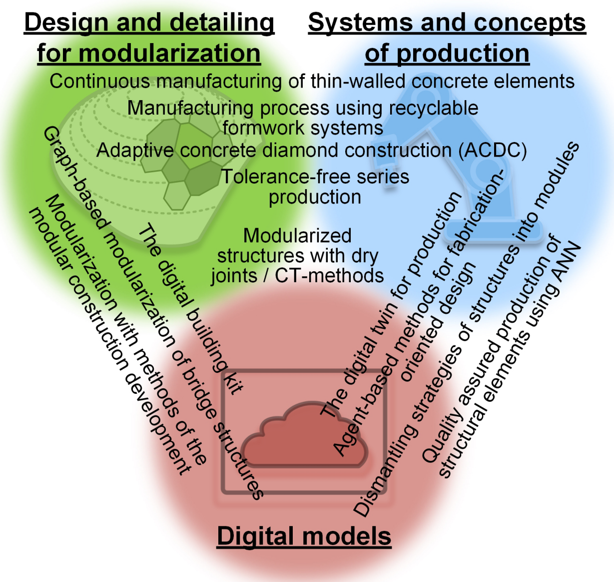

FIGURE 4 Project topics and classification into the three research fields (circles) (graphic: Patrick Forman)

The research program is divided into 12 individual projects, which are connected in their developments by means of three working groups and a central project. The working groups cover the three central research topics, namely:

- Design and detailing for modularization,
- Systems and concepts of production,
- Digital models.

Figure 4 shows the three thematic areas as colored circles and the projects with their short titles in their assignment. All projects are interdisciplinary and involve at least two subject areas.

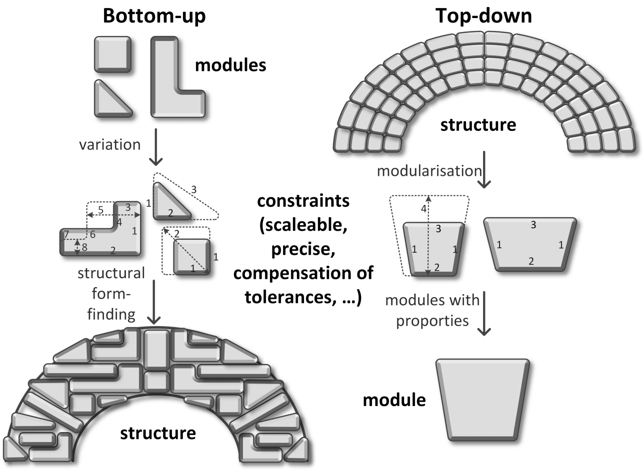

FIGURE 5 Merging of certain basic modules to form a structure (bottom-up) or modularization of a structure into new modules (*top-down*) (graphics: Patrick Forman)

In the following article, the three topics are discussed in detail and the individual developments are presented in terms of their goals and initial results.

3 | DESIGN AND DETAILING FOR MODULARIZATION

Today, modular construction is characterized by the prefabrication of entire structures or partial structures, such as garages, subsystems of residential buildings or elements of entire high-rise buildings. Prefabricated single-family houses consisting of a few massive modules are already being erected within just one day.[13] Timber construction modules, which form functionally fully equipped residential cells, are "stacked" to form the overall supporting structure.[14] Concrete ceilings as classic precast concrete elements are also already prefabricated with integrated building technology.[15] The driving force here is the saving of costs and time. According to Reference 16, modular construction in this form already offers time savings of up to 50% as well as a cost reduction of about 20% compared to conventional construction methods. Nevertheless, these modules are massive (several tons) and are mostly prefabricated by hand. The design is determined by the later function.

In contrast, design and detailing in SPP 2187 is subject to a clear paradigm: precise fast-track construction of the future can only succeed with stationary fabrication and flow production methods. Therefore, the subdivision of structures and components into transportable modules, which are ready for a plain assembly on the construction site, is mandatory. The design approach must be focused on modularization itself – and this must be done with a holistic standard.

However, modularization here does not mean a modular system with large and heavy "prefabricated parts", such as in industrial hall construction. The modules are not "ready-made," but they are adaptive during production, that is, they can be adapted to the respective requirements "on the fly" within previously defined limits (*mass customization*).[17] Only such adaptive modules can meet the demand to create individual and esthetic building structures. For this innovation, two essential factors enable a quantum leap compared to the developments of the 1960s: The use of Ultra-High Performance Concrete (UHPC) with corrosion-free reinforcements and the continuous digitization of the processes under the buzzword Industry 4.0. Thanks to the new and precisely adjustable material, slimmer components and novel joints without corrosion protection can be realized.[18] Digitization, on the other hand, enables the individualization of the components, the management of production with continuous quality control, and interactive feedback to the design in an overall planning model.[19] The implementation of *Building Information Modeling* (BIM) also provides a tool for monitoring the entire life cycle of the structure, including operation and recycling.[20]

In principle, two approaches to modularization can be distinguished (Figure 5). Either a set of known modules is the starting point for the overall structure (*bottom-up*) or a given structure is broken down into sufficiently small modules (*top-down*). In both cases, the manufacturing process, namely the limits of production, transport, and assembly, determines the design space.

Several subprojects have identified assembly on the construction site as a critical design factor and consequently place the last step of the production at the beginning of their considerations (*design for assembly*).[21] Technically, joints, especially dry joints, are weak points in traditional concrete construction and should be avoided if possible. In modular construction, they are the ubiquitous standard case and must be included into the design process with regard to scalability, precision, and tolerance compensation.[22] The challenge is to use quality controls and measurements not only randomly, but to integrate them continuously into the production process and to feed the results back into the planning. The goal is, for example, an automation in which deviations in the dimensions of individual modules can be compensated by adjusting the manufacturing parameters of subsequent modules.[23] If successful, this procedure is "tolerance-free," which means that within the completed structure, all deviations from production will neutralize each other. In this respect, the design task is comprehensive since it must also shape the layout of the overall process. Of course, this can only succeed if the design itself is also subjected to a certain modularization. A key to this is the parametric modeling of the components with corresponding optimization routines.

As the interface between the modules, the formation of the joints, whether dry or bonded, requires special attention both functionally and in terms of design. Depending on the modularization method, the contact points must meet different requirements for force transmission, such as normal forces, shear forces, moments, and combinations of these. Suitable joining principles and joint designs have to be developed for this purpose, which also may place previously unimaginable demands on precision.[22] In this context, non-corrosive tendons made of carbon can be used for force transmission and allow dry joints without further corrosion protection.[24]

If we now consider the modules themselves, which have to be moved quickly, precisely, and automatically in serial flow production, the load-bearing capacity of the industrial robots required for this purpose sets an upper limit on the modules' mass of ~1 ton. This limitation does not mean that the modules should be planned as small as possible. However, it is imperative to designing in a force-flow-oriented, light, effective, and thus material-saving way.[25] Voluminous and block-like modules have little chance of meeting the quest for resource-saving constructions. Planar or truss-like structures are sought after. Because of the defined and reproducible production conditions, it is also perfectly possible to increase the geometric complexity of the individual components according to the requirements.

It is well known that one of the biggest impediments in traditional concrete construction is the need to produce the formwork for the casting molds. It, therefore, makes sense to consider in particular processes that do not require any formwork at all, such as extrusion-based selective material deposition (additive concrete construction). In this process, the fresh concrete is deposited in a geometrically defined manner as a so-called filament with the aid of an extruder nozzle.[26] If, in a first assumption, the deposition is made on a flat base surface, a modularization of double curved shell structures into planar facets is necessary – actually a domain of so-called gridshells made of steel and glass. Obviously, the discretization of free forms with the methods of discrete differential geometry belongs to the canon of topics. Equally promising is a link to the work of the BLOCK Research Group (BRG) at the ETH Zurich, where essentially compression-stressed vaults made of relatively small individual parts demonstrate the performance of modular constructions (Figure 6).[27,28]

FIGURE 6 Armadillo vault by BLOCK research Group at the Biennale 2016 (Venice) (photograph: Anna Maragkoudaki)

The basis for such faceting, for example with planar quadrilateral facets (PQ-mesh), can be force-adaptive concrete shells similar to those of Felix CANDELA, Ulrich MÜTHER, Heinz ISLER and others (Figure 7). The procedure can be easily transferred from roof structures to so-called shell bridges.[29] For example, a subproject is dedicated to a graph-based decomposition of bridge structures into surface elements.[30]

In the end, in addition to the modularization (outer module geometry), all designs also have to define and parameterize the individual module elements (inner module geometry) as well as the coupling of the module elements with each another. A “digital construction kit” is desirable, in which static-mechanical aspects as well as simulation (order of assembly) and sensitivity analysis of the modules and the overall system can be mapped.[31]

4 | SYSTEMS AND CONCEPTS OF PRODUCTION

Building is a highly individual process today, just as it was a few decades ago. Buildings and structures are planned as one-offs and

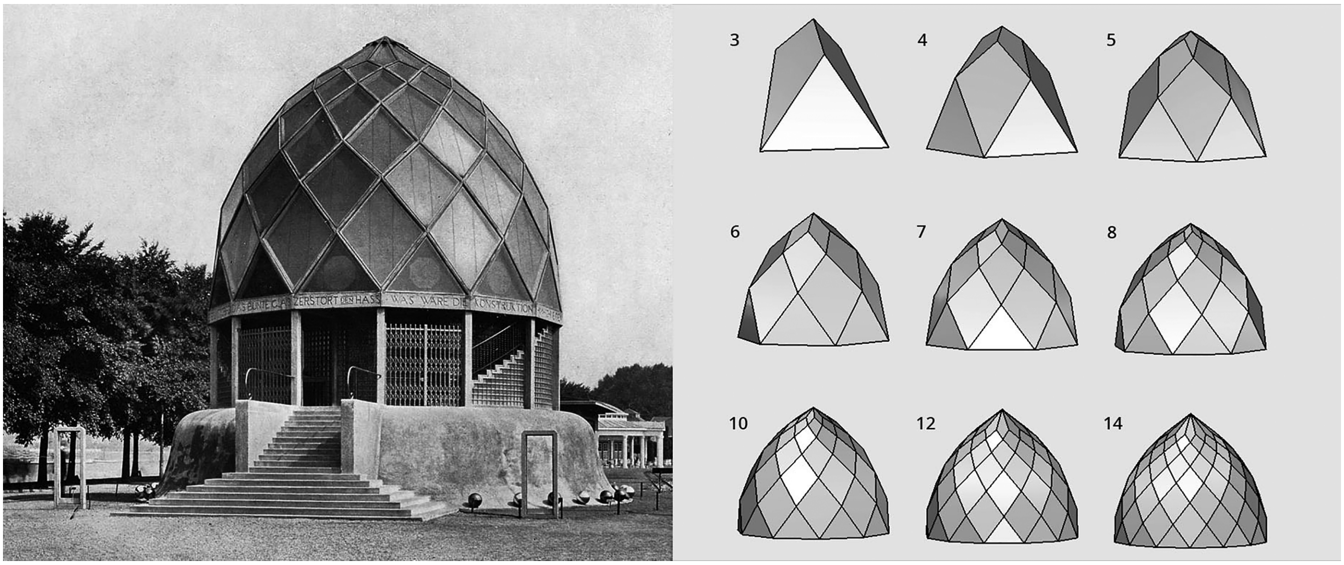

FIGURE 7 Remarkable quadrilateral faceting of the dome of Bruno Taut's glass house pavilion with a reinforced concrete ribbed construction and flat glass surfaces (Cologne Werkbund exhibition, 1914), parameter study of the design space (Daniel Lordick, 2018)

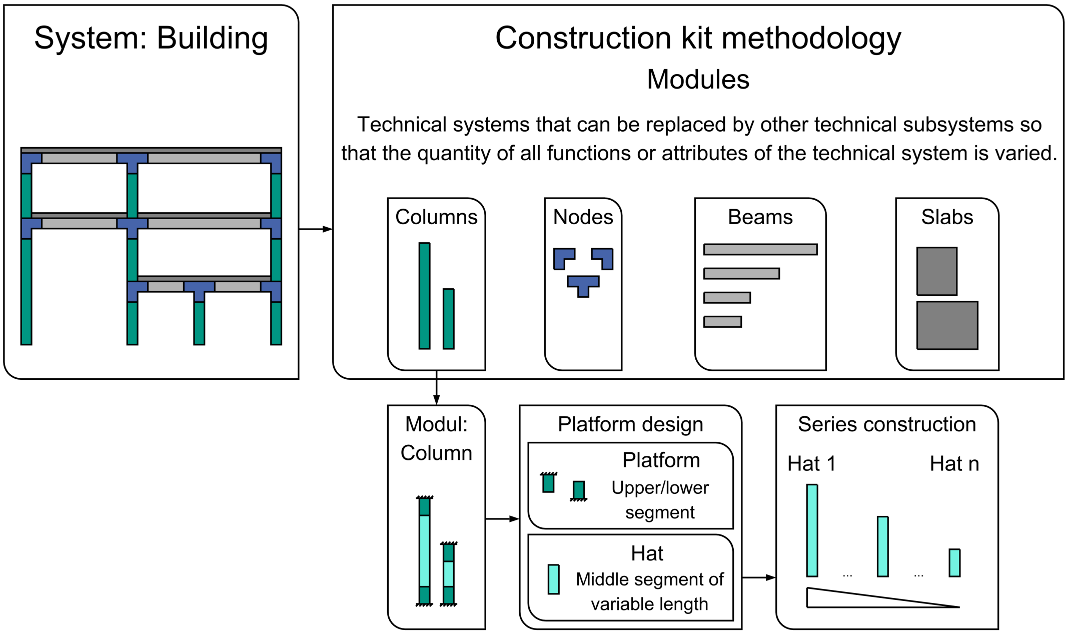

FIGURE 8 Fractal nature of the standardization method: Example of a building construction (figure: Agemar Manny)

constructed from components developed specifically for this building, which means that—at the expense of construction costs and construction time – the customer's needs can be specifically addressed. One approach to reduce construction costs and time despite individual customer requirements are standardization methods such as the construction kit methodology and platform design from mechanical engineering. These methods enable the reuse of component and building design. At the same time, the standards developed through their application form the basis for leveraging economies of scale along the entire product life cycle and, in particular, in the value creation process.[32]

A construction kit is defined in Reference 33 as an abstract construct that contains all those subsystems (modules) from which different systems (structures) can be configured (Figure 8). In addition to the modules and their variants, the construction kit also includes an associated set of rules that describes the nature of the subsystems – with particular attention to the interfaces – and thus ensures compatibility between the systems.[33] In order to ensure the exchange of individual module variants (e.g., different module geometries), clearly defined and standardized interfaces are absolutely essential, especially for complex systems.

A platform design is given, as described in Reference 33, if the subsystems can be differentiated into "platform" and "hat." In this context, the platform comprises all subsystems that are used repeatedly and unmodified across different systems. However, the individual subsystems do not necessarily have to be physically connected to each other. The hat includes the remaining subsystems, which can differ across systems and thus create a range of variants. The concept of platform and hat is illustrated in Figure 8 (below) using the example of a column.

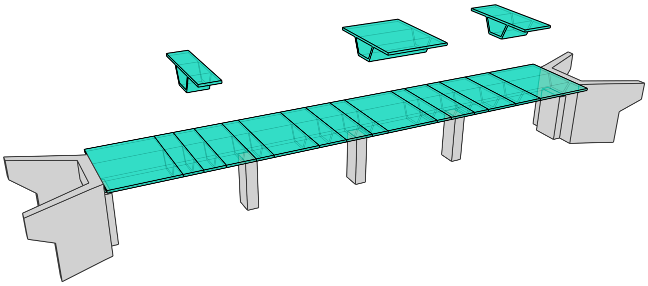

FIGURE 9 Modular structure of a box girder bridge (graphic: Agemar Manny)

The fractal character of standardization methods in particular allows a high degree of flexibility in the design of systems with controllable complexity of the components to be provided. For example, the modules within a modular system can be constructed according to the platform design, which in turn can be variably designed in different forms.[34] The example of a box girder bridge in Figure 9 serves as an example of the fractal nature: The hollow box can be realized by interconnecting the segment module variants existing in the modular system, as is common practice in the match cast process. For modularization in the sense of the priority program, however, the individual modules have too high dead loads and are not suitable for serial production using the flow production principle.

By transferring the two methods to civil engineering and developing them further, the goal of individualized structures (external diversity) with a low number of module variants (internal diversity) at the same time is being pursued. By limiting the amount of module variants to a small number, high repetition rates can be achieved for each module, enabling highly productive series production, as it is, for example,

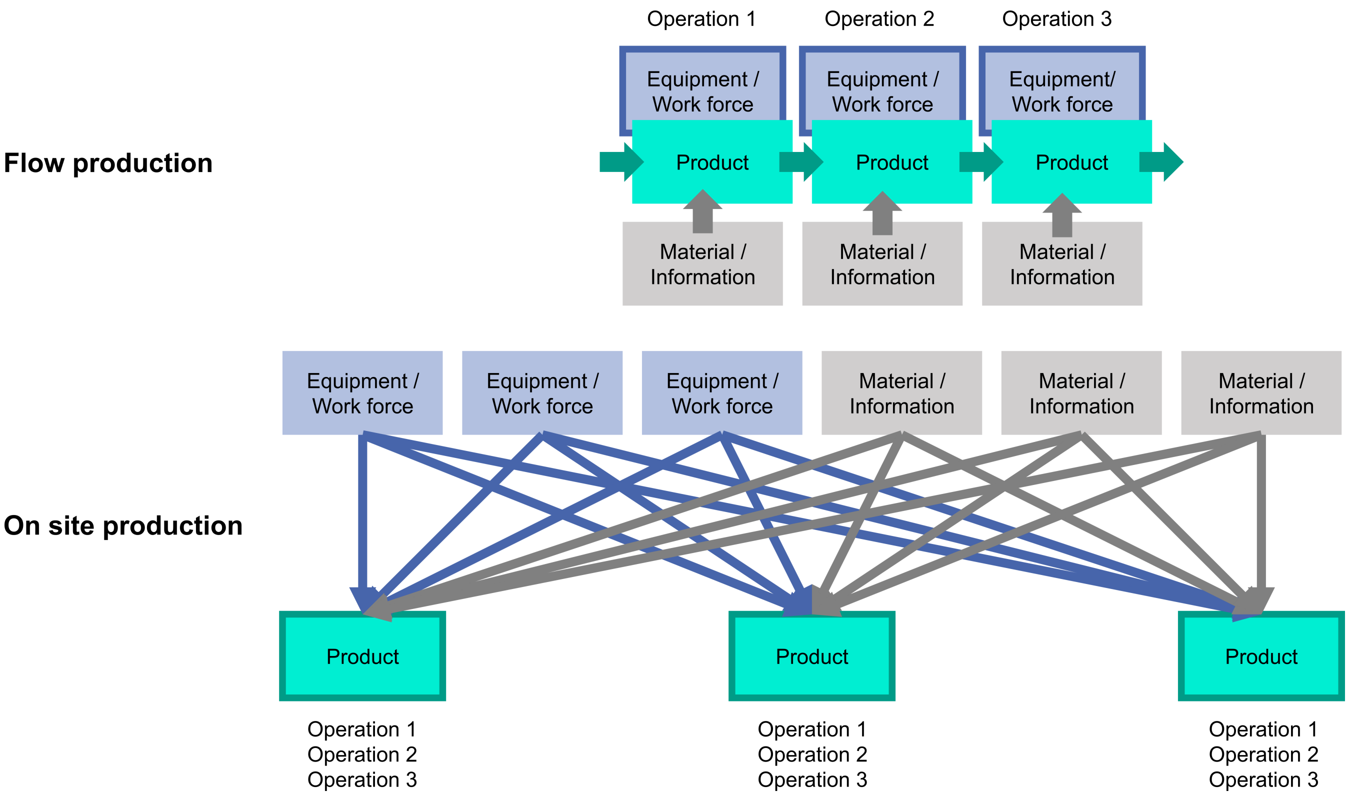

FIGURE 10 Comparison of flow and on site production following[37] (graphic: Alex Frey)

common in the automotive industry. The design of series production in mechanical engineering today largely follows the approach of holistic production systems. This is a set of rules for the design of production processes[35] that is based on the principle of lean production, that is, production that avoids waste such as unnecessary transport operations, inventories, or rework. The use of lean production is associated with numerous advantages such as, in particular, higher productivity and shorter lead times.[36] A typical design principle of holistic production systems that can be applied to the production of concrete components is the flow principle. During production, the component is moved in a line through fixed work stations arranged according to the operations to be performed (Figure 10, above). This principle of process organization contrasts with the usual stationary or site production in the construction industry, in which a stationary component is manufactured using moving production equipment (Figure 10, bottom). Efficiency increases by a factor of >2 when changing to the flow principle which can for example, be shown for the SYNCHRO production system at the company Trumpf.[37]

Eliminating waste improves quality as well as production time and costs. The introduction of the zero defect principle as part of holistic production systems also helps to create an awareness of defect prevention.[35] Eliminating defects in processes and products is the best way to reduce costs and improve lead times and customer satisfaction. Quality assurance becomes an integral part and is closely linked to production planning.[37]

The modular design places particularly high demands on the dimensional accuracy of the components to be manufactured. If a modular structure is subjected to a tolerance analysis, the dimensional deviation of the entire system results from a superposition of the dimensional deviations of its individual components.[38] The more components the structure comprises, the more sensible this effect is. Quality assurance is therefore an essential part of the processes which have to be (further) developed for the production of precast concrete components. The aim here is to achieve the shortest possible quality control loops by measuring and feeding back quality data inline. Specifically, off-process and off-machine quality control loops are to be used, that is, the measurement data are either collected after the processing operation in the same processing station (off-process) or in subsequent measuring stations (off-machine) and fed back into the process control[39] (Figure 11).

To avoid rejects of “inaccurate” components during production and assembly, the concept of so-called selective assembly, which is well known from mechanical engineering, can be used. This concept is used, for example, in the production of assemblies in the automotive industry with particularly high dimensional accuracy requirements, such as diesel injectors. Selective assembly is used to compensate for variations in actual dimensions occurring in the production process, for example with adaptive manufacturing in conjunction with individual assembly.[40] Here, components to be assembled of type A are manufactured in such a way that, statistically, they produce the best possible fit with previously manufactured parts of type B. For example, a shaft with oversize reduces the fit clearance to a hole with oversize. In modular structure construction, the modules are placed in the overall structure in such a way that dimensional deviations known

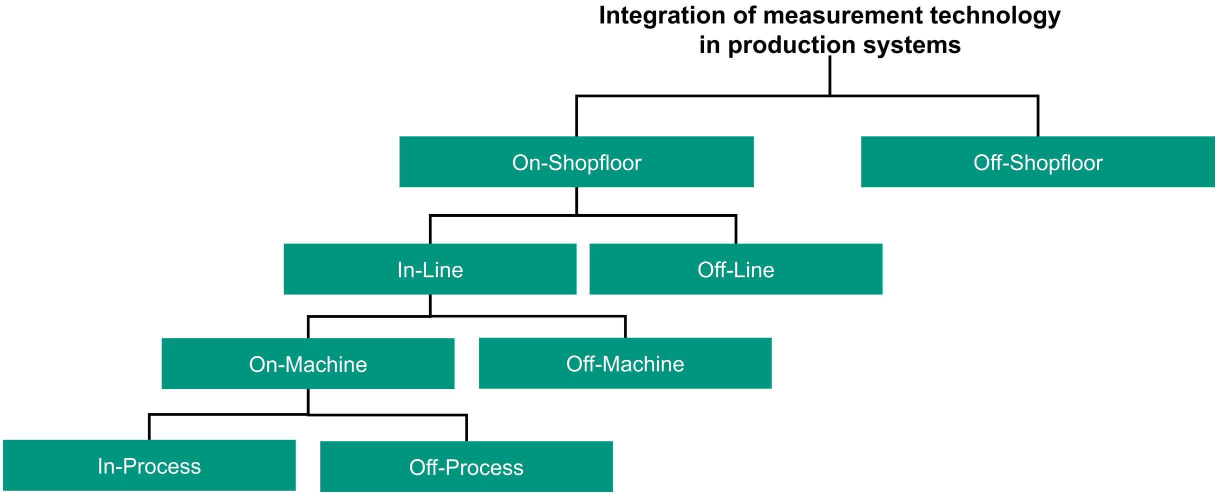

FIGURE 11 Integration of measurement technology in production systems according to Reference 39 (graphic: Gisela Lanza)

from *in-line* measurement are compensated locally if possible. Production and module design then merge into a single unit.

In this way, novel approaches for the efficient production of modular load-bearing structures are created by adapting methods of industrial series production.

5 | DIGITAL MODELS

Digital design using concrete has enabled the viable construction of complex structures which would otherwise only have been possible with a great amount of craftsmanship and correspondingly high costs. Digital design provides the basis for additive methods such as 3D concrete printing (eg, see References 41–43). Also, formwork construction,[44] segmentation methods, and joining principles[22,45] could be improved by digital design, which opens up new possibilities especially for classical concrete casting methods.

One of the key factors for the increasing productivity and efficiency of today's manufacturing is the use of information and communication technologies (ICT) in the entire product development process. Development times for new products can be shortened through early and focused communication, agreement, and coordination between design and production. For the quick and precise production of adaptive modules made of freely formable high-performance materials, relevant data concerning the production process as well as the current status of the module must be continuously recorded, collated, and made available. Based on this digital information, the individual production steps can be coordinated more precisely and the utilization of the machines can be better planned. An important prerequisite for the realization of continuous digital models, also known as digital twins, is the combination of the current concepts of Building Information Modeling and proven methods from Industry 4.0, which envisage largely self-organized production through the integration of digital tools and automated production technology.

Building Information Modeling stands for a cooperative work method using digital building models for various tasks in the life cycle of a building.[20] The focus of international research and development is to support the design, execution, and operation processes. To support the involved stakeholders, several methods have been developed for the various tasks. These include the management of heterogeneous information sources,[46] the digital exchange of experience,[47] automated collision checks,[48] the creation of construction schedule simulations,[49] the integration of energetic analyses,[50] and the use of models during the service phase.[51] In the field of design, production, and assembly of precast concrete elements, digital building models are already being used in several ways. In the area of planning the focus is, on the one hand, how to describe precast concrete elements geometrically as simply and reusable as possible[52] and, on the other hand, how to implement production processes optimally, taking into account variations in production technology. Initial approaches to the integration of external information for the control of the production process have also already been conceptually considered.[53]

Industry 4.0 is characterized by the interaction of products, services, processes, and organizational structures using innovations from the fields of information and communication technology.[54] The aim is to enable the manufacture of highly individualized products tailored to customer requirements without having to compromise automation or efficiency. The products and production systems that cause this paradigm shift are often described as cyber-physical (Cyber-Physical System – CPS and Cyber-Physical Production Systems – CPPS) or smart (Smart Product – SP). In the context of Industry 4.0, three different environments are considered. In the human world, people in the value creation process face the challenge of having to interact with components. Components are products, production plants, aids, and documents. The information world is further subdivided into the areas of models (meta models, technical models such as function plans, operational plans, business process descriptions), states (measured values, target values, configurations), and archives with descriptions of changes to the aforementioned things in the course of the life cycle.

A prerequisite for the desired level of interoperability in the context of Industry 4.0 is the introduction of a uniform digital representation, the so-called digital twin, for each type of product. The administration shell model from the Industry 4.0 reference architecture model can be used for this purpose. Every so-called asset is designed, created, used, and disposed of and is thus subject to a life cycle. An asset is a tangible or intangible object with value for the organization, regardless of whether it is a tangible product, a software component, or a service. The information on an asset is stored digitally in the associated administration shell and made available for man-machine and machine-machine communication, so that an Industry 4.0 component is created as a combination of an asset and its administration shell. The digital twin is thus the fully integrated digital representation of a physical product, where changes in the information world result in changes in the real world and vice versa.[55] Figure 12 shows the transfer of the basic principle of the digital twin to the modular design with supporting structure, its module division, the production system, and the administration shell with interaction modeling. It remains to be said that in the field of mechanical engineering, Industry 4.0 components can describe themselves, are networked, can provide and retrieve services and carry entire data collections over their life cycle. For the vision of a fast and precise production of concrete modules in industrial style, these properties form an excellent basis.

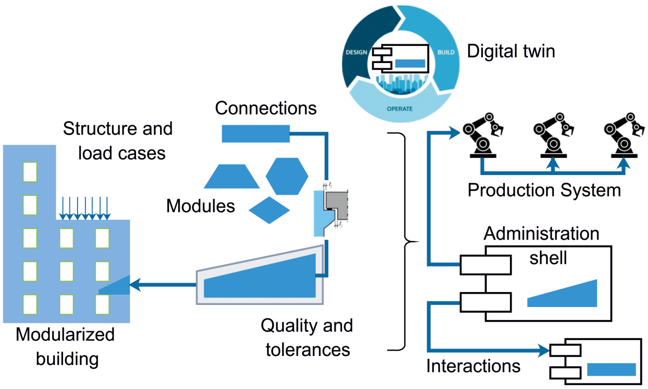

FIGURE 12 Illustration of concrete modules as administration shells for construction digital twins.
Source: Detlef Ger-hard & Markus König

Within the framework of SPP 2187, consistent and adaptable data and interaction models for the industrialized, fault-tolerant rapid production of modules made of freely formable high-performance materials are being developed on the basis of current progress in the field of Building Information Modeling and Industry 4.0. Based on a systematic collection of all relevant information and interactions in the form of ontologies, descriptions for digital twins of the modules under consideration are being developed that are suitable for the application purpose. A formal and testable description of the requirements with regard to function and quality, taking into account the possible uncertainties in the course of production, is essential. For this purpose, information from other products, systems, and processes must be collected, integrated, and analyzed. Based on these interactions with other objects, it is then possible to continuously check the requirements. Context-specific visualizations and navigation options are being developed so that information, states, and requirements can also be provided transparently for the participants involved.

Here, in the sense of Industry 4.0, the modules are to communicate with the respective production machines and other modules in the context of production. Based on the recorded data, it is possible to check at any time whether the current status of the module still meets the previously defined requirements. In the event of deviations, the data can be used to check whether the module can be reused elsewhere or to make corrections automatically. Ultimately, agile control of the planning and production of the module is enabled by this context sensitivity. Based on the findings from mechanical engineering and the research activities in the context of Industry 4.0, real-time networking of products, processes, and systems based on consistent data must take place for innovative adaptive module construction with flow manufacturing methods.

All sub-projects of the SPP develop and use specific interacting Industry 4.0 components or administration shells for their problems. On the basis of these consistent digital models, parametric modeling of the supporting structure is made possible, concepts for intelligent modularization are developed, simulations and sensitivity analyses of the modules and their constructive connections are implemented,

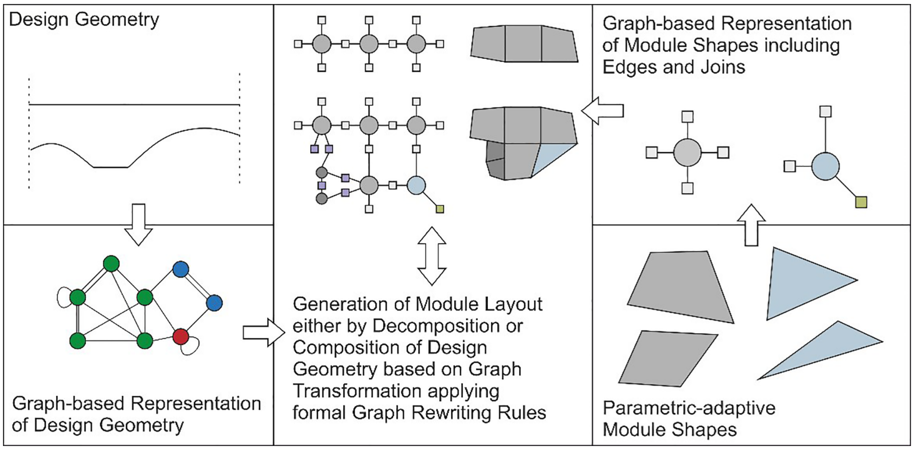

FIGURE 13 Generation of a modular layout based on graph-based representations (graphic: Simon Vilgertshofer)

production system variants are generated with the help of parametric approaches, and also the digital control of the production of precision concrete elements is realized. Through the uniform use of data and the development of digital interaction chains, completely new methods for the production of adaptive modules from high-performance concrete in industrial flow production can be developed. Figure 13 illustrates two approaches to a module definition based on graph theory. In the top-down approach, a given design geometry is analyzed and transformed into a digital graph-based representation. Subsequently, shape finding can be initiated by formally decomposing the design geometry using formal graph transformations. In the bottom-up approach, on the other hand, the concept is pursued by combining existing, parametrically described modules in such a manner that they come as close as possible to the design geometry. Here, too, graph transformations are used to assemble the entire system.

6 | CONCLUSION

Time becomes the decisive factor of building in existing context in Germany and Europe – rapidness is the guiding principle. It is necessary to drastically reduce restrictions on the traffic flows of infrastructures due to long construction periods. Therefore, the modular construction presented here relies on consistent quality-assured prefabrication with serial character and rapid construction on site lasting only a few days, controlled by a digital twin. In essence, it is about transferring and implementing the methods of lean production and Industry 4.0 to the construction industry. Costly human labor, unnecessary material consumption, waiting times, and traffic jams as well as inaccuracies and errors are prevented. The result is a holistic, low-waste construction process, which is only possible through the methods of digitization. The main conclusions are:

- The advantages of serial production such as weather independence, precision in geometry and material, production speed, or seamless quality control can be used for any supporting structure made from concrete. The key is to segment the structure into many similar modules.
- The fabrication principle can be used for modularized structures as well as for a priori mass production ready (repetitive) components such as segmental linings[56] or solar thermal collectors.[57]
- In contrast to classical prefabricated building, the individual components (modules) are smaller, much lighter, and have a hundredfold repetition.
- Established concepts in mechanical engineering, such as lean production and construction kit methodology, enable to ensure the required quality and geometrical accuracy.
- Individualized serial production is only possible with complete digitization (digital twin) of all process steps. Only consistent, end-to-end digitization ensures the quality and interoperability of the individual steps from production through assembly to the time of use and, if necessary, deconstruction and recycling.

First benchmarks and interaction chains to quantify possible savings in costs, time, material, and CO_2 emissions as well as accuracy limits are currently under development while first demonstrators have already been built up.

ACKNOWLEDGMENT

The authors thank the German Research Foundation (DFG) for the financial support of their projects in the framework of the priority program 2187 (grant number 402702316).

ORCID

Patrick Forman https://orcid.org/0000-0001-8292-7966

REFERENCES

1. Hong J, Shen GQ, Feng Y, Lau WS-T, Mao C. Greenhouse gas emissions during the construction phase of a building: A case study in China. J Clean Prod. 2015;103:249–S. 259. https://doi.org/10.1016/j.jclepro.2014.11.023.
2. Mehta PK. Reducing the environmental impact of concrete: Concrete can be durable and environmentally friendly. Conc Int. 2001;23(10):61–66.
3. Mark P, Neugebauer P. Erhalt unserer Bausubstanz. In: Bergmeister K, Fingerloos F, Wörner J-D, editors. Betonkalender 2015, Hrsg. Berlin: Ernst & Sohn, 2015; pp. 1–24.
4. Department of Economic and Social Affairs – United Nations (2019) World Population Prospects 2019, United Nations, New York
5. Rodrigues FA, Joekes I. Cement industry: Sustainability, challenges and perspectives. Environ Chem Lett. 2011;2:151–166. https://doi.org/10.1007/s10311-010-0302-2.
6. Suhendro B. Toward green concrete for better sustainable environment. Procedia Eng. 2014;95:305–320. https://doi.org/10.1016/j.proeng.2014.12.190.
7. Mark P, Lanza G, Lordick D, et al. Vom Handwerk zur individualisierten Serienfertigung - Schwerpunkt adaptive Modulbauweisen mit Fließfertigungsmethoden. Bautechnik. 2021;98(3):243–256. https://doi.org/10.1002/bate.202000110.
8. Greinacher S, Overbeck L, Kuhnle A, Lanza G. Multi-objective optimization of lean and resource efficient manufacturing systems. Prod Eng. 2020;14:165–176.
9. Gaganelis G, Mark P. Downsizing weight while upsizing efficiency – An experimental approach to develop optimised ultra-light UHPC hybrid beams. Struct Concr. 2019;6:1883–1895. https://doi.org/10.1002/suco.201900215.
10. Forman P, Gaganelis G, Mark P. Optimierungsgestützt entwerfen und bemessen. Bautechnik. 2020;97(10):697–707. https://doi.org/10.1002/bate.202000054.
11. Gaganelis, G.; Forman, P.; Mark, P. (2021) *Stahlbeton optimiert – für ein Mehr an Weniger* in: Handbuch Nachhaltigkeit, Ressourceneffizienz und Klimaschutz; Hauke, B./Institut Bauen und Umwelt e.V./DGNB e.V. (Hrsg.), Ernst & Sohn, Berlin.
12. Tkocz J, Mark P. Heat treatment and shrinkage steering of precast thin walled concrete tubes. In: Derkowski W et al., editors. Concrete – Innovations in materials, design and structures, fib symposium 2019, Krakow, 2019; pp. 2246–2253.
13. https://www.icon-haus.de/modul-bauweise/1-tag-1-haus.html ([cited 2021 Jan 15])
14. Huß W, Kaufmann M, Merz K. Building in timber - room modules. Detail Practice, 2019.
15. Friedrich T. Wie sehen Betonfertigteile und die zugehörigen Bau- und Produktionprozesse in Zukunft aus? BWI – BetonWerk Int. 2018;2:154–163.

16. Bertram, N.; Fuchs, S.; Mischke, J.; Palter, R.; Strube, G.; Woetzel, J. (2019) Modular construction: From projects to products. McKinsey & Company, June 2019.
17. Koren Y. The global manufacturing revolution: Product-process-business integration and reconfigurable systems. Hoboken, New Jersey, John Wiley, 2010.
18. Voo YL, Foster S, Pek LG. Ultra-high performance concrete – Technology for Present and Future. In: Hordijk DA, Lukovic M, editors. High tech concrete: Where technology and engineering meet, 2017 Proceedings of the 2017 fib Symposium. Maastricht, Netherlands, June 12–14, S. xxv-xlii.
19. Colledani M, Tolio T, Fischer A, et al. Design and management of manufacturing systems for production quality. CIRP Ann Manuf Technol. 2014;63:773–796.
20. Borrmann A, König M, Koch C, Beetz J. Building information modeling – Technology foundations and industry practice. Springer International, 2018.
21. Kao GT-C, Körner A, Sonntag D, Nguyen L, Menges A, Knippers J. Assembly-aware design of masonry shell structures: A computational approach. In: Bögle A, Grohmann M, editors. Proceedings of the IASS Annual Symposium 2017 25th–28th September. Germany: Hamburg, 2017.
22. Mainka J, Lehmberg S, Budelmann H, Kloft H. Non-Standard Fügeprinzipien für leichte Bauteile aus UHPFRC. Beton- und Stahlbetonbau. 2013;108(11):763–773.
23. Stindt J, Frey A, Stricker N, Mark P, Lanza G. Kopplungsmethoden von Entwurf und Produktion zur toleranzfreien Serienfertigung. BetonWerk Int. 2021;2:20–21.
24. Schlaich M, Simon S, Rettinger M, Gänz P, Guhathakurta J. Modularisierte Tragstrukturen aus nachträglich vorgespannten Carbonbetonbauteilen auf Basis von Trockenfugen und Computertomographie. BetonWerk Int. 2021;2:19–20.
25. Scheerer S, Curbach M. Leicht Bauen mit Beton. Forschung im Schwerpunktprogramm 1542. Förderphase 1. Dresden: Institut für Massivbau, Technische Universität Dresden, 2014.
26. Mechtcherine V, Lordick D. Schalungsfreie Fleißfertigung adaptiver Tragstrukturen. BetonWerk Int. 2020;5:16–17.
27. van Mele T, Mehrotra A, Mendez Echenagucia T, et al. Form finding and structural analysis of a freeform stone vault. In: Kawagu-Chi K, Ohsaki M, Takeuchi T, editors. Proceedings of the International Association for Shell and Spatial Structures (IASS) symposium 2016, September. Tokyo, Japan, 2016.
28. Block P, Van Mele T, Liew A, DeJong M, Escobedo D, Ochsendorf J. Structural design, fabrication and construction of the *Armadillo Vault*. Struct Eng. 2018;96(5):10–20.
29. Schlaich M. Shell bridges – And a new specimen made of stainless steel. J Int Assoc Shell Spatial Struct 2018;59(3):215–224.
30. Fischer O, Borrmann A, Auer D, Afzal M. Brückenbauwerke mit komplexer geometrie durch facettierte flächenelemente aus carbonbewehrtem ultrahochleistungsbeton. *BetonWerk Int.* 2020;5:18.
31. Bekel D, Bletzinger K-U. Der digitale Baukasten – Simulationsbasierte Modelle und Methoden für den Entwurf modularer Tragsysteme aus Beton. BetonWerk Int. 2020;4:16.
32. Meier, J. (2007) *Produktarchitekturtypen globalisierter Unternehmen*. Dissertation Techn. Hochsch. Aachen, Aachen: Shaker.
33. Albers A, Scherer H, Bursac N, Rachenkova G. Model based systems engineering in construction kit development-two case studies. Procedia CIRP. 2015;36:129–134.
34. Albers, A., Bursac, N., Wintergerst, E. (2015) *Product Generation Development – Importance and Challenges from a Design Research Perspective* in: Proceedings of INASE Conferences 2015.
35. Dombrowski U, Mielke T. Ganzheitliche Produktionssysteme: Aktueller Stand und zukünftige Entwicklungen. Berlin, Heidelberg, Springer-Verlag, 2015.
36. Staufen AG.: *25 Jahre Lean Management: Lean Gestern, Heute und Morgen*. Available from: https://www.staufen.ag/fileadmin/HQ/02-Company/05Media/2-Studies/STAUFEN.-studie-25-jahre-lean-management-2016de_DE.pdf [cited 2020 Nov 16]
37. Kammüller M. Synchrone Produktion im Werkzeugmaschinenbau. In: Spath D, Westkämper E, Bullinger HJ, Warnecke HJ, editors. Neue Entwicklungen in der Unternehmensorganisation. Berlin, Heidelberg: Springer Vieweg, 2017. https://doi.org/10.1007/978-3-662-55426-5_49.
38. Rausch C, Nahangi M, Haas C, Liang W. Monte Carlo simulation for tolerance analysis in prefabrication and offsite construction. Autom Constr. 2019;103:300–314.
39. Lanza G, Haefner B, Schild L, et al. In-line measurement technology and quality control. Metrology (Precision Manufacturing), Singapore: Springer Nature, 2019; pp. 1–35.
40. Wagner R, Kuhnle A, Lanza G. Optimising matching strategies for high precision products by functional models and machine learning algorithms. WGP Annals. 2017;7:231–240.
41. Mechtcherine V, Nerekka VN, Will F, Näther M, Otto J, Krause M. Large-scale digital concrete construction – CONPrint3D concept for on-site, monolithic 3D-printing. Autom Constr. 2019;107:102933.
42. Kloft H, Empelmann M, Hack N, Herrmann E, Lowke D. Bewehrungsstrategien für den Beton-3D-Druck. Beton- und Stahlbetonbau. 2020;115(8):607–616.
43. Wörner M, Schmeer D, Schuler B, et al. Gradientenbetontechnologie. Beton- und Stahlbetonbau. 2016;111(12):794–805.
44. Mainka J, Kloft H, Baron S, Hoffmeister H-W, Dröder K. Non-Waste-Wachsschalungen: Neuartige Präzisionsschalungen aus recycelbaren Industriewachsen. Beton- und Stahlbetonbau. 2016;111(12):784–793.
45. Lehmberg S, Ledderose L, Wirth F, Budelmann H, Kloft H. Von der Bauteilfügung zu leichten Tragwerken: Trocken gefügte Flächenelemente aus UHPFRC. Beton- und Stahlbetonbau. 2016;111(12):806–815.
46. Becerik-Gerber B, Ku K, Jazizadeh F. BIM-enabled virtual and collaborative construction engineering and management. J Profess Issue Eng Educ Prac. 2012;138(3):234–245.
47. Alashwal AM, Rahman HA, Beksin AM. Knowledge sharing in a fragmented construction industry: On the hindsight. Sci Res Essay. 2011;6(7):1530–1536.
48. Han N, Yue ZF, Lu YF. Collision detection of building facility pipes and ducts based on BIM technology. Adv Mater Res. 2012;346:312–317.
49. Haque, M.E., Rahman, M. (2009) *Time-Space-Activity conflict detection using 4D visualization in multi-storied construction project* in: International Visual Informatics Conference 2009. Bridging Research and Practice, Visual Informatics, 266–278.
50. Gupta A, Cemesova A, Hopfe CJ, Rezgui Y, Sweet T. A conceptual framework to support solar PV simulation using an open-BIM data exchange standard. Autom Constr. 2014;37:166–181.
51. Lin YC, Su YC. Developing mobile-and BIM-based integrated visual facility maintenance management system. The Scientific World Journal, 2013;124249.
52. Sacks S, Eastman CM, Lee G. Parametric 3D modeling in building construction with examples from precast concrete. Autom Constr. 2004;3:291–312.
53. Zhong RY, Peng Y, Xue F, et al. Prefabricated construction enabled by the internet-of-things. Autom Constr. 2017;76:59–70.
54. Monostori L, Kádár B, Bauernhansl T, et al. Cyber-physical systems in manufacturing. CIRP Annals. 2016;2:621–641.
55. Kritzinger W, Karner M, Traar G, Henjes J, Sihn W. Digital twin in manufacturing: A categorical literature review and classification. IFAC-PapersOnLine. 2018;51(11):1016–1022.

56. Smarslik M, Mark P. Hybrid reinforcement design of longitudinal joints for segmental concrete linings. Struct Conc. 2019;20(6): 1926–1940. https://doi.org/10.1002/suco.201900081.
57. Forman P, Penkert S, Kämper C, Stallmann T, Mark P, Schnell J. A survey of solar concrete shell collectors for parabolic troughs. Renew Sustain Energy Rev. 2020;134:110331. https://doi.org/10.1016/j.rser.2020.110331.

How to cite this article: Mark P, Lanza G, Lordick D, et al. Industrializing precast productions. Civil Engineering Design. 2021;3:87–98. https://doi.org/10.1002/cend.202100019