Graph-based mass customisation of modular precast bridge systems – Methodology for kit development and algorithmic design

Lothar Kolbeck, Simon Vilgertshofer, André Borrmann
Technical University of Munich, Germany
lothar.kolbeck@tum.de

Abstract. Modular construction is a method to respond to the high demand on bridge facilities while encountering a pressing need to reduce resource consumption and to respond to shortage of skilled labour. By standardising systems through modular parts and their interfaces, scale effects can be reached and related manufacturing and planning processes can be industrialised. Regarding design, the automated generation of high-quality product models usable for various downstream applications becomes economic. Allocated in this context, this contribution presents an algorithmic design approach for the mass customisation of a modular precast bridge system. Particular requirements to be abided are, first, the construction with small-scale and lightweight precast elements to leverage flow production and, second, the adaptability of the system and modules to a range of height profiles and alignments, and third, the design with aesthetic and complex geometries. The developed methodology and a case study are presented including construction kit development, related parametric product modeling and algorithmic mass customisation.

1 Introduction

Since the establishment of reinforced concrete construction, industrialising fabrication and construction has recurrently been a goal for engineers. However, it has been difficult to develop systems that prove to be economic yet convince owners, architects and societal environment by diverse design qualities. Currently, a new wave of research and development aims to create modular precast systems that reach scale effects while receiving the acceptance of the stakeholders. A viable approach can be the use of small-scale, parametrically adaptable modules with relatively simple geometry which are digitally fabricated in flow production lines and then assembled into more complex systems with esthetic shapes (Mark et al. 2021). Compared to individualised precast concrete fabrication, modular approaches may reach scale effects by mass customising an adaptable construction kit system for many individual projects. Standardisation and scale effects in turn allow a significantly higher level of automation – in production yet also in planning and design.

Design processes can be rationalised by developing software for the automated mass customisation of high quality product models, assuring that the various constraints of the system are met given the individual project setting. Essential advantages of such “configurators” are the avoidance of time-intensive and repetitive manual drawing as well as the assurance of model quality for downstream applications such as structural analysis or fabrication information generation. In the following article, we contribute to this area by providing a suitable design automation methodology. First, we present a concept to develop and formalise an adaptable modular precast system bridge system abiding various requirements. Second, we propose how to translate a construction kit architecture into a suitable product modeling concept. Third, we introduce suitable strategies of data and algorithm modeling to automate the product model generation for complex geometries and topologies.

2 Related Work

In the stationary industry and related mechanical engineering, a rich body of products and theory for modular system architectures is present (Krause & Gebhardt 2018). In this sector, processes of system construction are well established and followed strategically, so that even advanced topics such as product generation management or cross-product modularity are taken into consideration (Albers et al. 2015). In the contemporary building sector, system construction is merely a (growing) niche. Few systems and products are established: Stiff frame structures have a long, persistent history (Elliott & Hamid 2017) and since a few years increasing interest in room-module based residential housing systems can be observed (Winter 2018; Singh, Sawhney & Borrmann 2019). Buildings with complex geometries and structural systems however so far remain in the individualised precast segment, in spite of promising research activities (Hierl & Tresch 2021). A further expansion of modular construction in the building sector is demanding, because of the many small- and medium scale stakeholders, a frequent separation of planning and execution as well as the high cultural value western societies assign to individualised architecture. Despite this complex setting, the advantages of modular construction motivate to sensitively react to these diverse requirements and to develop suitable technology.

Regarding the information technology applicable for algorithmic design, parametric and product modeling systems play a key role. State of the art tools implement techniques such as feature-based modeling, constraint solvers and hierarchical assembly management (Shah & Mäntylä 1995) to make complex models and design processes controllable. Based on such fundamentals, first investigations on the limits and potentials of automating model-based design date back to the early 2000s (Sacks, Eastman & Lee 2004). As a basis of automation, a variety of use-case specific product modeling concepts have been proposed. For bridge design, especially the alignment-oriented parametric modeling concept of Obergrießer (2017) is relevant to our contribution. The concept described is relatively flexible and has been adopted similarly by commercial bridge modeling tools.

For varying topologies of systems and complex geometric computations, the above mentioned core functionalities of product modeling tools do not suffice to streamline and automate all design and detailing processes occurring in a mass customisation process. In these cases, algorithms need to model an additional layer of logic to substitute time-consuming and error-prone direct modeling and computation processes. In the construction sector few publications, all related to room-module based housing, treat business processes and software architectures for mass customisation (Cao et al. 2021) as well as data modeling and interoperability issues (Gan 2022). Related mainly to mechanical and mechatronic engineering, there is a wider set of algorithmic design studies. The field of formal engineering design synthesis (Antonsson & Cagan 2009) attempts to explore and structure methods to automate computer-based design processes, studying academic examples as the classic coffee maker with a variety of methods as for example graph grammars (Tonhäuser & Rudolph 2017).

We lent some ideas on business process outline, data modeling and software architecture from above mentioned sources, but focused on developing a comprehensible and scalable approach custom to the characteristics of modular bridge systems. Related principles of kit development, product modeling and algorithmic design are introduced in the following section.

3 Algorithmic Design Concept

3.1 Business Process Context

Any design can be seen as synthesis of manifold requirements into a physical structure. For bridge systems, we recommend to differentiate requirements regarding design, structural, production and (dry) assembly. An example for a design requirement is the desired spanning width range, a structural requirement is the maximally allowed bending moment for a certain cross section, a production requirement the allowable length and weight of modules and an assembly requirement example the needed tolerances. Such requirements need to be systematised and met by a system construction idea that allows reaching scale effects in planning and production in many projects. Thereby, construction kit development is a conceptual work that starts by decomposing a system into standardised modules and module interfaces. Parallely, adaptable concepts of structural proofing, production and assembly need to be developed which are adaptable to the range of designs. This schematic, conceptual work lays the foundation to exploit scale effects by mass customising the system in multiple project settings. For design purposes, parametric concepts and suitable algorithms may automate the product model generation and other pieces of software may automate processes of analysis and proofing or fabrication information generation according to the developed concepts. The interplay of requirements, kit development and mass customisation is visualised in figure 1.

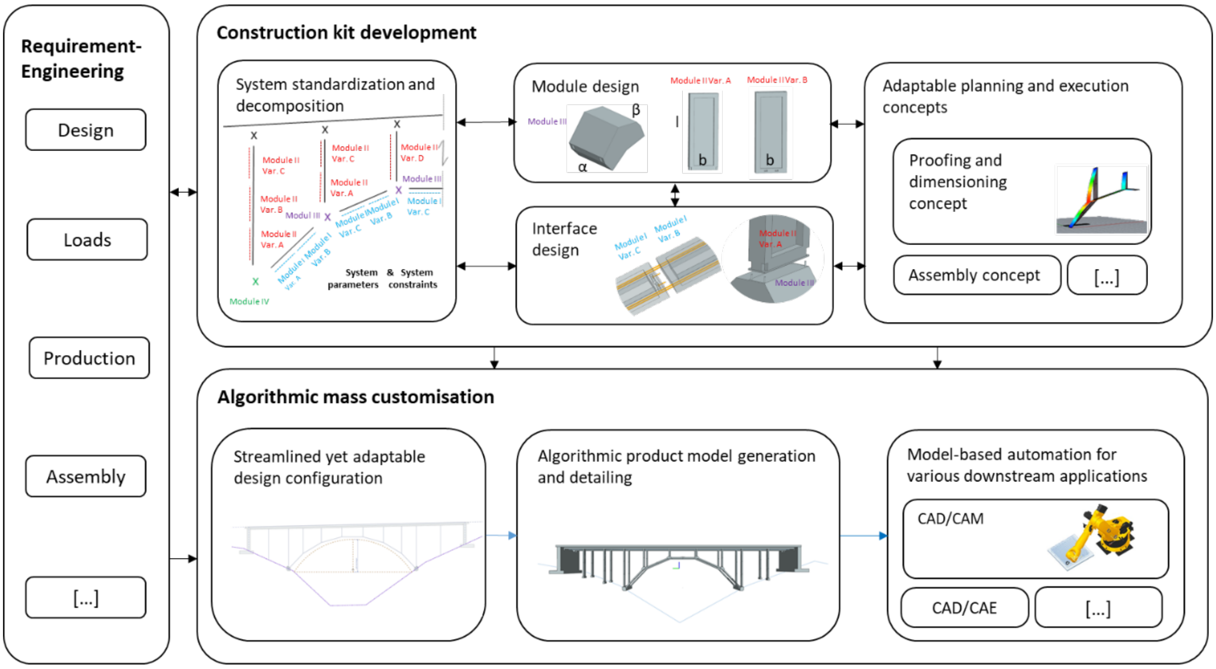


Figure 1: Process overview of construction kit development and mass customisation

The following sections introduce suitable concepts for system construction development and related algorithmic mass customisation for modular precast bridges.

3.2 Modular Construction Kit Design Concept

At the start of the kit development process, among all possible requirements and samples, according to our experience it is recommendable to start by a structured deliberation of design requirements. Questions to be answered are the range of boundary conditions to be covered, the scope of the system for a building and to derive the necessary need to adapt the system and modules during mass customisation. Further, a client for the "product" to be developed needs to be clear in order to outline business processes and downstream processes and to understand the extent of planning and execution services that can be streamlined in-house. Useful resources to consider are existing standardisations, e.g. regular cross sections or reference drawings for highway bridges. Statistical analysis may help to delimit requirements, e.g. by analysing databases or models of existing buildings (Cao & Hall 2021).

After clarifying design requirements, we find it useful to explore the structural system to be applicable. The chosen system needs to be decomposed into systems and systems with clear internal and external structural connection points of the subsystems. According to the structural behaviour and interfaces, a first compilation of cross-sections and interface details may be created, e.g. deciding the use of external prestressing cables and form-locking profiles for double-T-segments with pinned support at the abutments. We propose to start formalising the kit definition with a catalogue-like structure noting fixed and adaptable features, interfaces, structural behaviour and extending the obtained knowledge by adding information about manufacturing or assembly processes. Given an initial kit draft, a first iteration of kit design can be concluded by discussing implications of interface detailing, analysis, fabrication, assembly and software systems with respective domain experts. Many iterations and explorative, experimental studies are commonly necessary, as the technical complexity is much higher compared to conventional, craft-based construction projects. Only in the end of a long and iterative development process, software experts can build on sufficiently defined details and technical processes to automate planning and design processes.

3.3 Product Modeling Principles

A product model with high depth of semantic, topologic and geometric information is the basis of state of the art digital planning and fabrication processes. For a given design model, downstream processes like structural analysis, cost calculation, fabrication information derivation may be automated if sufficiently high and standardised model quality is achieved.

Regarding the topological-semantical organisation of the product model for our use case, we propose to adapt the generic principles described in Obergrießer (2017): The assembly should be hierarchised with two organisational levels steering the mass customisation by adaptable, auxiliary sketch geometry and adaptable, hierarchically propagated parameters. The auxiliary geometry on the highest level is a steering sketch adaptable to depict variable alignments and topography. Subordinated to those organisational levels, we find the introduction of further three levels useful: On the third level, modules are grouped as far as it makes sense to group multiple modules, e.g. for fabrication or analysis processes. The fourth level of hierarchy consists of single modules, the fifth level are components oriented relative to one single modules such as certain interface components (e.g. plugs or plates) or reinforcement elements.

Regarding the geometric modeling of modules, we highly recommend following object-oriented principles in part and procedural parametric modeling. It is recommendable to model one part per module. Part families should be used to create project-specific instances of modules, with one part per configuration with different sets of adaptable parameters. Proper naming conventions of parts help designers and manufacturers and should include the type of module, interfacing modules and adapted parameters. For such a given structure, feature-based procedural parametric modeling allows to handle high complexity when describing the module geometries. Samples following the given principles may be studied in the part file folder published with the referenced software prototype (Kolbeck 2023).

3.4 Algorithmic Mass Customisation Concept

Part descriptions and a product model structure provide the basis for mass customisation. This requires the abstraction in the form of a data model representing the essential design entities with their essential interdependencies. We recommend that reasoning in terms of graph theory is useful to organize the information structure. A (property) graph model should be built, strongly leaning to the before defined product model structure. Organising nodes, e.g. the substructure or an arch, should be introduced to hierarchise information and should be initialised depending on the topology and geometry of the steering sketches. Modules should be modeled as separate nodes with edges indicating aggregations to the containing nodes and edges indicating design dependencies, e.g. coincident points, with other modules.

For algorithm design, we found it useful to distinguish and encapsulate different types of algorithmic processes: First, processing steps for the steering sketch, second the distinction of the computation of the number, types and the adaptable parameters of entities, resulting into an according transformation of the graph. Third, the creation or update of parts and part families and, fourth, the semantic-topologic transformation the product model assembly. We recommend to follow object-oriented modeling principles when encapsulating these types of computation processes and to separate the data model from the mass customisation algorithm. Organised according to these principles the computational design process is an iterative process of topology transformation, part processing and assembly extension, depending on the system-specific design logic.

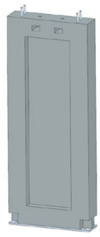
4 Case Study on Arch Bridge System

4.1 Construction Kit Architecture

It was decided to experiment the methodology for a construction system for underdeck arch bridges because of their demanding shape and because of the structural suitability of arches for dry module interfaces which are known to be sensitive to tension and shear forces. The scope was delimited to substructure and foundations. As design requirements, 30 to 40 meters of arch span width were determined, with a two-lane deck and columns left and right of arch to be able to cover a variety of alignment situations and max. 1.0 to 12.0 meters of column height. This setting is plausibly applicable to many smaller valley bridges and medium-sized rivers in Germany.

As a structural system, we intended to design the arch structure allowing rotation freedom at the foundations and on both ends of the columns in order to reduce momentum for a more filigree structure. For dry interface, the use of steel bar prestressing, pin-connections and composite construction plates were considered. To formalise the development process, we catalogued the required modules with a strong focus on interfaces and the mentioned concept of standardised adaptability. Table 1 shows the standardisation result for two of the mainly used panel-like modules with material-saving voidings in the centre of the module.

Table 1: Proposed catalogue form for standardisation efforts, illustrated for two panel-like modules

Module name	Interface details	Adaptable parameters	Visualisation	[…]
Arch Panel Type 1 Interfacing Foundation Type 1 & Arch Panel Type 2	60 mm traverse bolt for pinned support embedded in concrete, 35 mm ducts for constructive prestressing, 35 mm shear bolt at top, 100 mm x 60 mm x 160 mm rectangular voiding for insertion of shear bolts, […]	2.0-3.5 m length, 35-55 cm lower rib width 5-15 cm shell thickness […]		[…]
[…]	[…]	[…]		[…]
Column Panel Type 1 Interfacing KneeJunctionModule & Column Panel Type 2/3	25 mm anchorage plate embedded in concrete with 30 mm welded prestressing bolts, 35 mm ducts for constructive prestressing, 2x 100 mm x 60 mm x 160 mm rectangular voiding for shear bolt anchorage, […]	1.0-3.5 m length, 5-15 cm shell thickness […]		[…]

As mentioned in Section 3.2, other aspects should be incrementally included in the standardisation, e.g. foreseen flow production processes, assembly procedures or critical structural proofs. Abiding the requirements discussed in section 1 and distinguishing modules according to structural behavior and interfaces, the substructure required the standardisation of seven panel-like modules and one knee-junction module to compose the kit.

4.2 Product Model Structure

For the structure of the model, we followed the five hierarchy levels proposed in section 3.3. The upper two propagate shape and topology of the system adaptable within the height profile and alignment, propagated parameters include e.g. the bar tendon diameter or the thickness of the panel-like modules. The lowest two levels contain components and (interface-relevant) embedded elements. The bar tendons fulfill an interface functionality but were modeled on the module level as they connect multiple parts and could not be positioned relative to a single module. A snippet of the entire model structure is presented in Figure 3.

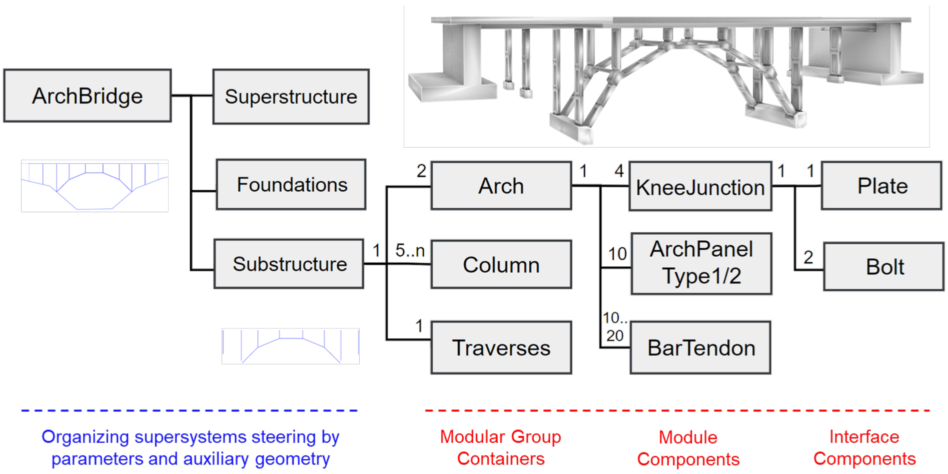


Figure 3: Snippet of assembly hierarchy for arch bridge system showing logic

This model structure proved useful for the automation of design model generation. The algorithm developed to this end is described in the following.

4.3 Algorithmic Mass Customisation

In order to encapsulate the four types of computational design processes mentioned in Section 3.4, functions regarding the processing of auxiliary geometry, topology computations, part manipulations and product model interaction were encapsulated in four classes with methods that differentiate the treatment of different subsystems. All methods transform a graph model constituted of eleven types of design entity nodes modeled: Five container node types (*Substructure*, *SubsystemArch*, *SubsystemArchSegment*, *SubsystemColumn*, *SubsystemModularGroup*) were modeled as well as six node types describing concrete modules (*ModuleArchPanel*, *ModuleKneeNode*, *ModuleColumnPanel*, *ModuleTraverse*, *Tendon*, *Support*). Categories of modules were grouped into single node types, the module type is expressed as a property that the algorithm reacts to. Figure 5 illustrates the incremental evolution of the product model and the corresponding development of the graph.

The property graph is built using instances of .NET classes and the edges by references between those instances. The given topologic complexity did not make the use of dedicated tooling (such as graph libraries) necessary. In case of future persistency needs of the information compiled during the algorithmic design process, the serialisation of the graph would however be possible and straightforward. Algorithm and data model have been coupled to the software *NX Design* as an established product modeling tool for bridge design; the modeling software is however exchangeable with any other tool offering the CAD-functionalities described in section 3.3.

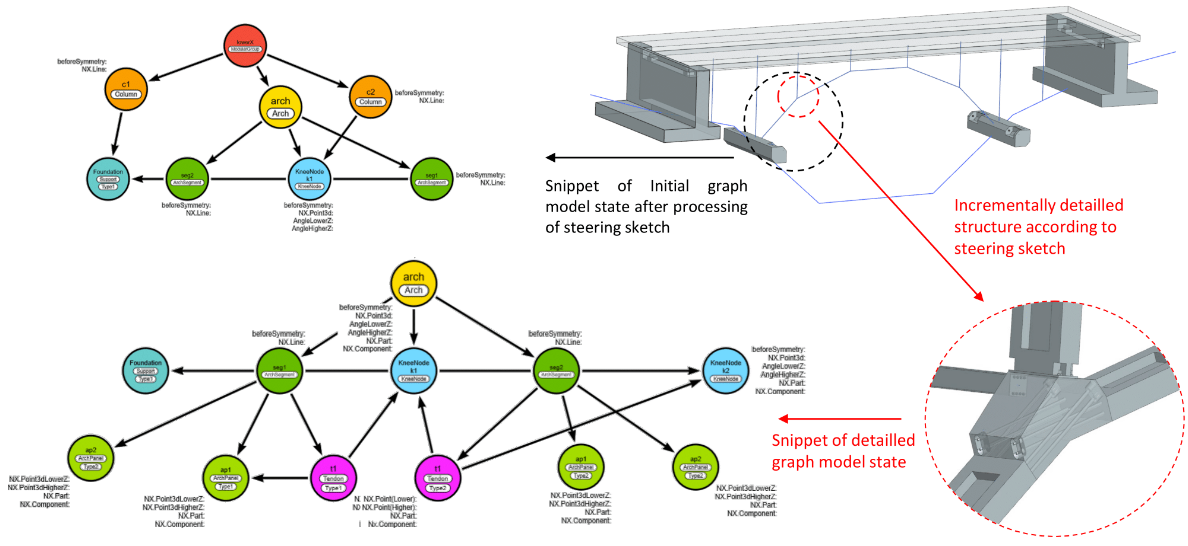


Figure 5: Incremental, algorithmic mass customisation process with evolving product model (re.) and corresponding graph representation (le.), illustrated by snippets

The data structure and the algorithm presented can be modified with little effort to include different subsystem modularisations, module variants to vary the structural system or the interface connections. Figure 6 shows the degree of flexibility the mass customisation prototype currently allows, with varying height profiles (top) and varying system geometries (bottom). The four models illustrate that the prototype allows a rapid system adaptation to different topographic settings and the comparison of system customisations for one given topography.

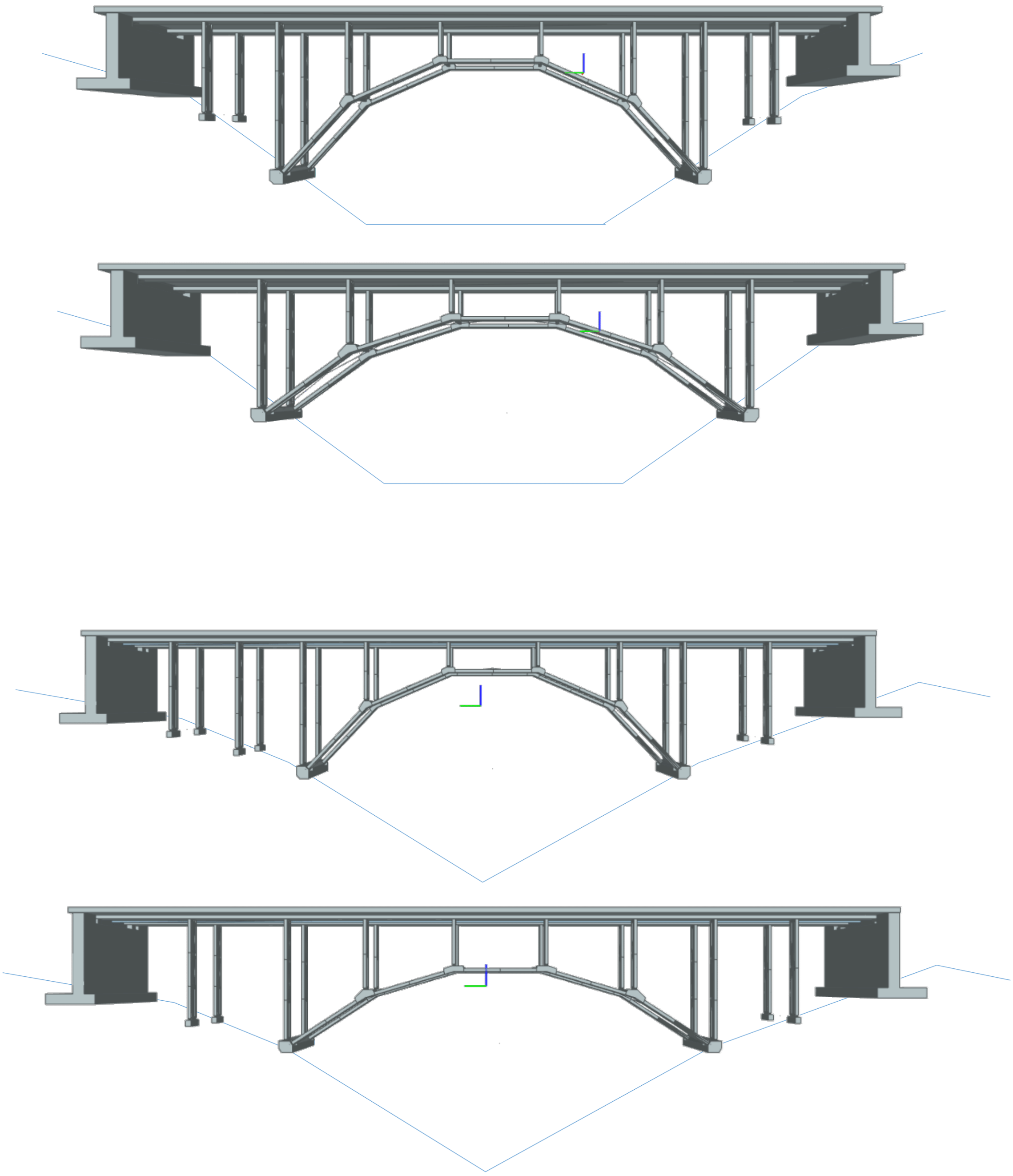


Figure 6: Degree of flexibility allowed by the mass customisation approach shown by two topologically and geometrically different variants for two different height profiles.

For further details on the algorithm and the product model, the published code is available open-source (Kolbeck 2023). The four models shown above are included in the repository in IFC-format.

5 Discussion

This paper showed that modular precast involves a standardisation of (adaptable) parts and interfaces to obtain scale effects. The scale effects leverage and allow automation in manufacturing and planning processes. For design purposes, the algorithmic creation of high-quality product models is feasible and arguably even necessary. As a prerequisite, it requires a comprehensibly documented standardisation as well as a product modeling concept capable of hierarchising and controlling topologic, semantic and geometric complexity for a variety of project settings. Graph theory is useful to abstract the design entities and their relations to find a computational representation for the incremental assembly and detailing. To streamline the algorithmic approach, the graph model should lean closely to the product model structure. For automation, pieces of logic such as procedural parametric part modeling may be handled well by the product modeling authoring tool, core of algorithmic reasoning should be tasks such as the computation of topology, semantics and adaptable parameters as well as complex geometric processes. Those processes require the flexibility and control structures offered by application programming interfaces.

The presented method and implementation focuses on informatics aspects and thus is not exhaustive regarding other affected engineering disciplines. Exemplarily, this implies that the kit and dry interfaces may certainly be improved or replaced by other modularisation ideas, that detailed design may be adopted and automated according to detailed concepts of dimensioning and proofing or that the modules may be optimised regarding flow production processes. We think that the algorithmic design method is mature and conceptually flexible enough to be adaptable to a variety of other modular precast systems. However, we think that this transfer requires a flexible and fundamental understanding of product and data modeling principles. In this regard, we think that our method could be further generalised and formalised to streamline comparable automation approaches for engineers trained only with basics of informatics.

6 Outlook

For a further generalisation and streamlining of the proposed algorithmic modular design method, we intend to abstract our approach by applying the principles of formal engineering design synthesis (Antonsson & Cagan 2009). We intend to adapt a graph grammar based approach to describe and conduct the assembly of modules and their connectivity via a set of rules. The other types of algorithmic design processes distinguished in this contribution we plan to formalise by dedicated entities in a formal process modeling approach. The goal is to enable a visually graspable setup of the algorithmic process that supports engineers by predetermining software architecture and framing necessary programming work. As this contribution showed, the automation of mass customisation processes is based on the ability to formalise and synthesise knowledge from interdisciplinary engineering domains, e.g. connection or fabrication technology. We think that the construction sector currently lacks methodology to frame the early phases of such research and development processes. The document-based approaches leave a lot of room for ambiguity and pose challenges for the desired automation via model-based planning methods. To remedy these shortcomings, we aim to adopt Model-based Systems Engineering methods which are wide-spread in the stationary industry. We plan to use those methods to conduct structured requirement engineering, system architecture and system interface design for the complex overlay of physical, fabrication and software systems involved.

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