Parametric Structural Design for automated Multi-Objective Optimization of Flexible Industrial Buildings

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Abstract -

Individual customer needs and accelerating technological advances in Industry 4.0 are leading to rapid manufacturing changes, thus industrial buildings need to accommodate constantly evolving production processes. The load-bearing structure acts as crucial limiting factor regarding the building's flexibility. As structural performance is highly linked to other design-disciplines, there is a need for integrated computational solutions allowing for performance-oriented structural design and optimization in early-design stage.

In order to address these issues, this paper presents the framework development of an early-stage parametric structural optimization and decision support model for integrated industrial building design. The framework combines architectural, structural, building service equipment and production process planning parameters and evaluates the impact of changing manufacturing conditions on the structural performance, automatically evaluating flexibility metrics to guide the decision-making process towards increased sustainable design. In a case study of ten real industrial construction projects, the interdependencies between discipline-specific data in industrial building design are analysed and collected in a graph data model. The proposed parametric framework is tested on a pilot project from the food production sector. Results validate the efficiency of the framework design and indicate that an optimization of the structural axis grid can save up to 25% of the material demand. A discussion on the results and next steps for further model improvement are presented.

Keywords –

Industrial building design; parametric modeling; performance-based structural design; multi-criteria decision analysis; early design stage; decision support

1 Introduction

Flexibility has become an increasingly important topic in industrial building design. Due to product individualizations, accelerating technological advances in manufacturing planning and shorter production lifecycles industrial buildings strive for highly flexible structures. The load-bearing structure, as the most rigid element with the longest service life in a building, is decisive for the adaptability and transformability of manufacturing systems. Flexible load-bearing structures, which can be implemented by means of wide-span girder systems and different load carrying capacities, can prolong the building's service life without expensive rescheduling measures.

The data and software needed by manufacturing planners differ by the ones from building design and are usually based on special discipline-specific knowledge. Multidisciplinary design teams involve conflicting views of different stakeholders and planning parameters and the prevalent uncertainty associated with multiple discipline-specific models. However, the production owner's demand should be satisfied by cooperating and assessing work of all planning disciplines. Compared with manufacturing services, building components have a much longer lifecycle, though buildings need to supply the interaction between production processes and machines, the building structure and service equipment. Effects of changing production processes on the building structure and consequently on the performance along the whole life cycle of the factory should be simulated and visualized in real time, giving reliable feedback on design-decisions already in early design stage. Therefore, a large quantity of data need to be integrated, although data availability in early design-stage is rare and data exchange between different disciplines rarely exist.

Integrated decision-making systems that provide manufacturing and building criteria is relatively complex, since currently production and building design processes run consecutively, lacking in feedback loops. Additionally, structural considerations usually enter the design process too late and are subservient to architectural and production goals, leading to suboptimal structures and inflexible floorplans. Thus, environmental and economic aspects such as resource consumption and life-cycle costs could be reduced by collaborative performance-based decision-support systems, optimizing the structural system. However, digital industrial building models do not properly address the interaction between production and building design disciplines, which may later lead to inflexible solutions.

In industrial construction projects, stakeholders are faced with numerous complex design decisions, involving the choice of conflicting variables such as different construction types, production processes or building service equipment (BSE). Multi-criteria decision analysis (MCA) taking into account possible scenarios of production layouts can help to improve the structural performance of production systems. Though, require maximum integration of all stakeholders and a vast amount of data in early design stage. To achieve this integration several architectural, structural and manufacturing aspects and their interrelations need to be considered and new computational strategies developed in order to generate applicable design solutions.

This paper presents ongoing research, conducted within the research project BIMFlexi, which aims to increase the flexibility of industrial buildings towards rapidly changing manufacturing systems in a BIM-based digital platform. This paper explores a novel approach integrating production process planning into performance-based structural design in early design stage of industrial buildings. A framework for a parametric structural design and optimization model in order to allow multi-objective optimization (MOO) with immediate decision support increasing the flexibility of industrial buildings is developed. The parametric model framework is designed to be integrated into the BIM-based digital platform of BIMFlexi in a next step of the research.

In this paper, we first review the state of the art for MCA in industrial building design. We then explore collaborative decision-making problems with focus on structural performance integration (chapter 2). In order to identify relationships between building design and production planning the results of a comprehensive case study, analysing ten real industrial facilities, are summarized in a graph data model. We propose a framework for a parametric structural performance-based design and optimization model that can be used by stakeholders involved in industrial construction projects to support in multi-criteria decision-making in early design stage (chapter 3). The framework is tested on a pilot project and results are discussed (chapter 4). The paper completes with a conclusion and outlook of the next steps. (chapter 5).

2 Literature Review

Research and industry community widely acknowledge the need for flexible and adaptable buildings, contributing to sustainable design choices [1]. Maximizing the flexibility of building structures can minimize costs and time required for rescheduling, but identification of interdependencies among discipline-specific systems bears challenges [2]. Cavalliere et al. [3] develop a BIM-based parametric model for automatic flexibility evaluation for sustainable building design.

Regarding MCA and decision-support systems for production plants, numerous research has been conducted in optimization of manufacturing systems [4-7]. A modular process model taking into account databased interdependencies in factory planning respecting the building is developed by Hawer et al. [8]. Yet, industrial buildings are rarely in research focus [9]. Among the conducted research, several authors proposed models concentrating on industrial building level. Kovacic et al. [10] develop a life-cycle analysis tool for facade-systems of industrial buildings, claiming that decision-making processes require long-term horizons, which, however, still need improvement. Authors in [11] develop an approach for factorial design space exploration supporting in multi-criteria decision-making (MCDM) to study energy performance, environmental impact and cost effectiveness along the life cycle. The author in [12] present a sustainability assessment methodology based on MCDM including factors influencing early design stage of industrial buildings. In [13] a study developed a decision-making model to describe relations between factory buildings, manufacturing equipment, sustainability aspects and the planning process. Other researchers focused on the prediction of the energy efficiency in production facilities [14] or used MCA for space heating system selection in industrial buildings [15]. Methods and models developed for MCA of industrial buildings mostly address energy performance improvement. Less attention is on the structural performance. However, to determine the overall efficiency of industrial buildings a concurrent assessment of the synergy effects of production processes, BSE and the building itself is needed [16].

Current available structural analysis tools are not sufficient for early design stage as their focus is rather on precision than flexibility often lacking in interoperability to other design tools [17]. Few structural analysis methods allow analysis and visualization in a single environment, provide feedback only to the structural engineer himself and do not support an integrated performance improvement [18]. Parametric modeling can support in conceptual design, enabling early integration of engineering-specific knowledge [19] allowing fast variant studies and enabling flexible exploration of design spaces by varying parameters and their dependencies [20]. Using parametric design tools such as Grasshopper for Rhino [21] or Generative Components [22] provide visual programming environments and allow the integration of structural performance simulations such as Karamba3D [23]. In addition, a number of computational tools supporting MOO are already embedded in traditional parametric modeling software [24], including the generative solver Galapagos [25] for Grasshopper.

Several methods have been used to support integrated design exploration for structural performance with MOO in conceptual stage. Authors in [24] present a case study of a cantilevered stadium roof for early-stage integration of architectural and structural performance in a parametric MOO design tool. In [26] a MOO methodology for structural efficiency and operating energy efficiency focusing on long span building typology is presented. [27] develop a design tool, which parametrically generates and semi-automatically analyzes truss designs with real-time visual structural performance feedback. Mueller and Ochsendorf [18] propose a computational approach in evolutionary design space exploration, combining structural performance and designer preferences. Pan et al. [28] propose a design process for long-span structures composed of a parametric model, a framework of interdisciplinary assessment criteria and MOO with post-processing tools.

The above listed research results are remarkable but focus either on production process modeling or building performance, mostly focusing on energy efficiency. Holistic models receive little attention. Indeed, the focus in early industrial building design should be on the optimization of the load-bearing structure in order to maximize the facilities flexibility, thus prolonging the buildings service life and reduce life-cycle costs.

Hence, this paper deals with the framework development of an early-stage parametric structural optimization and decision support model for integrated industrial building design. It integrates architectural, structural, BSE and production process planning and evaluates the impact of changing manufacturing conditions on the structural performance, automatically evaluating flexibility to guide the decision-making process towards increased sustainable design.

3 Research Methodology

As described in the previous chapter, this paper focuses on the investigation of the interdependencies between building (architecture, structure, BSE) and production (manufacturing program, machine layout and space requirements) data in order to develop a parametric multi-criteria model for structural optimization and decision support. Multi-criteria decision-making requires a vast amount of data in order to come to applicable results. The research is based on a case study to construct a network from direct empirical observations, showing graphical data structure, compactly representing dependencies.

3.1 Use-Case Study

The use-cases under investigation are selected acc. to [29] and are representative for the research objective. Due to different types of production examined – Automotive, Food and Hygiene, Logistic, Metal Processing and Special Products - a diversity is created and not exclusively the needs and objectives of a specific manufacturing sector investigated. The recommendations in [29] are followed with a total number of ten examined use-cases. The purpose of the research is to develop theory, not to test it. The use-cases are selected because the highest density of given information and the best accessibility of data and leading stakeholders was available [30]. Table 1 gives an overview of the examined use-cases.

Table 1. Use-Cases examined

Use-Case	Production Type	Floor Area [m²]	Primary Construction
A	Food	5760	Steel Truss
B	Logistic	5040	Steel Truss
C	Logistic	8064	Timber Girder
D	Metal	16200	Timber Truss
E	Automotive	160704	Steel Truss
F	Metal	2800	Steel Girder
G	Metal	28224	Precast RC Girder
H	Special	1296	Precast RC Girder
I	Metal	6750	Underspanned Timber Girder
J	Special	1992	Steel Truss

3.2 Graph Data Model

We have undertaken a process of creating a graph data model for the representation of interactions between production planning and building design to cover the requirements for the developed parametric model. A graph data structure is naturally defined around graphs, nodes and edges. In the conducted research an attributed graph is used for modeling, describing properties for nodes and edges [31]. The approach consists of two tasks: extracting generic hypothesis-evidence relationships from the case study, concentrating on design variables and parameters and organizing such relationships in a data structure to facilitate quick response using a minimal amount of memory and computational time later on.

The proposed Graph Data Model for integrated industrial building design (GIB) is structured as follows:

- *Nodes:* The design parameters in GIB system include geometric entities (i.e. structural elements), constraints (loads, legal restrictions) or other requirements (i.e. space requirements).
- *Labels:* The nodes are assigned in four labels according to the examined disciplines.
- *Edges:* define the relationship between the nodes
- *Properties:* Nodes or edges maintain a set of attributes (property values) thus allowing storing of relevant data and information.

Figure 1 shows the effective graphic representation of dependencies in integrated industrial building design combining the disciplines of production-, architectural-, structural-, and BSE planning based on the results of the case study. The proposed GIB model is grow- and changeable over time and relationships, nodes, properties and labels can be added or removed. The flexibility and simplicity of the graph data model allows reviewing of the data structure and serves as basis and modeling guide for the parametric script.

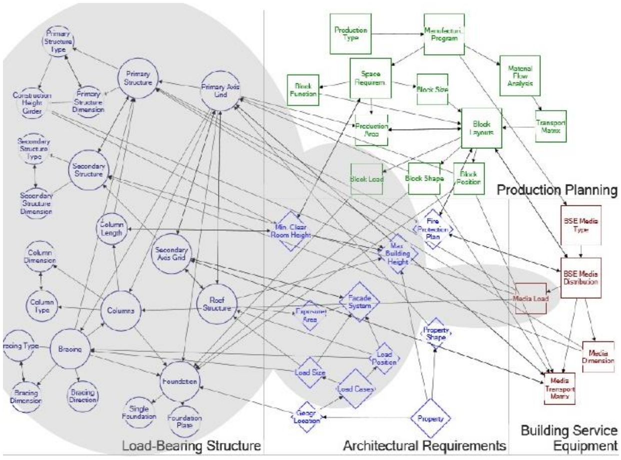

Figure 1. Attributed graph data model for integrated industrial building design (GIB).

Figure 1 additionally highlights the nodes that have already been considered in the status of the parametric framework in grey area. Missing parts, e.g. production- and BSE- entities will be integrated in the next step of the research.

3.3 Model Framework Description

In multi-criteria design analysis, the number of design-options is typically very large and the options not explicitly known. We have developed a framework for a parametric design process in Grasshopper for Rhino [21] in order to find options within the solution space and systemise the appropriate evaluation. Additionally, the Grasshopper components Karamba3D [23] for structural analysis and Galapagos [25] for evolutionary search are used in the parametric design process. Karamba3D allows early-stage structural design, form-finding, and structural optimization. Using a parametric script allows the automatic analysis and optimization of the load-bearing structure in consideration of constraints from other disciplines.

The framework consists of six discrete steps (see Figure 2) that in total comprise the parametric multi-criteria model for structural optimization and decision support:

1. Parameter & Input
2. Geometry & Loads
3. Element Definition
4. Structural Analysis
5. Structural Performance
6. Optimization

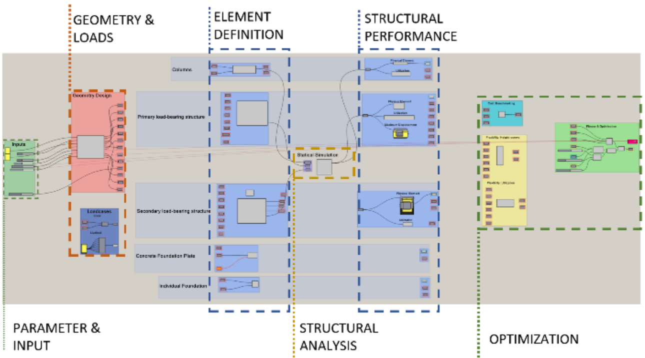

Figure 2. Framework of the parametric grasshopper model containing six steps.

In a first step, the definition of the building's typology takes place by selecting eight design inputs as described in Table 2. The load-bearing element-ranges are defined according to the case-study results.

Table 2. Input variables for the design process

Typology		
	Variable	Range
G1	Prim. Axis Grid (x-axis)	0 – 30m
G2	Prim. Axis Fields	1 – i
G3	Sec. Axis Grid -x	0 – 30m
G4	Sec. Axis Grid -y	1 – j
G5	Hall Headroom	5 - 15m
G6	Max. Building Height	5 - 20m
S1	Primary Structure Type	1-2
S2	Secondary Structure Type	1-2

The design variables for flexible structural industrial building design are defined as the position of the columns representing the axis grid in x- and y- direction, for both the primary and secondary structural system.

Furthermore, an important grid variable represents the z-direction as the free hall headroom inside the building and the outer maximum building height. The primary and secondary structure type can be chosen variable in a range of two pre-defined systems, which are either a truss (Option 1) or girder structure (Option 2).

Following, the base geometry is generated as a wireframe model, according to the definition of the axis grid. Simultaneously, pre-defined loads, obtained from the case study, such as snow load and live loads, dependent from production process and BSE-planning, are applied automatically.

In the third step, the structural elements are generated based on the generated wireframe model. Currently, following structural elements for modeling and calculation are taken in account:

- Primary load-bearing structure
- Secondary load-bearing structure
- Columns
- Bracing system
- Individual foundations
- Concrete foundation plate

After the generation of the structural system with associated elements, the structural analysis is carried out in the fourth step. The pre-dimensioning of the pre-defined elements considering input variables and load-cases takes place. The fitting of the cross-sections is executed with the native cross-section optimizer in Karamba3D.

In the fifth step, the structural performance is carried out. Since as-built structures often differ from idealized finite-element models for structural computation, the elements are re-arranged by considering structural design rules based on gained knowledge during the case study. For further processing, the structural performance is evaluated based on the criteria of utilization and maximum displacement.

The final step contains the calculation of constraints and objectives for design optimization. The optimization step uses Galapagos as an evolutionary algorithm to optimize the design alternative considering the fitness function, as described in the following section.

3.4 Fitness Function and Optimization

In order to allow the optimization of the input variables, the parametric script automatically calculates objectives and constraints of diverse design options. Table 3 shows the set of constraints and objectives considered in the fitness function. The considered constraints are the maximum utilization of the structural elements, the maximum building height and the maximum displacement of the structural system.

The pursued flexibility objectives are the minimization of the structural space requirements in the production hall (F1), the maximization of the free height reserve in the hall (F2), the maximization of the material saving (F3) and the minimization of the structural utilization in order to be able to place additional loads on the system in future without conversion work (F4). The presented objectives are a pre-selection based on a series of interviews with different discipline-specific stakeholders carried out during the case study.

The definition of the flexibility objectives for the fitness-rating is partly based on the method presented in [3], where distance- and percentage-based indicators are presented giving the possibility to determine the flexibility of design alternatives. The distance-based indicator serves for definition of the objective function F2 to maximize the height reserve of the system, whereas the percentage-based indicator is used for the objective functions F1 to minimize the structural space and F4 to minimize the utilization of the structural system. In addition, a reference-value based indicator is defined by putting obtained reference values of the material demand in different production types from the use-case analysis (i.e. average material demand of a structural system) in proportion to the actual material demand of the optimized system. The reference-based indicators serve for the calculation of the objective function F3 to maximize material savings.

Table 3. Constraints and objectives defining the fitness function for flexible industrial building design

Constraints		
	Constraint	Range
C1	Maximum Utilization ≤ 1,0	{0,1}
C2	Building Height ≤ Max. Height	{0,1}
C3	Displacement ≤ Max. Displacement	{0,1}
Objectives		
	Objective	Range
F1	Minimize Structural Space *percentage-based*	{0:1}
F2	Maximize Height Reserve *distance-based*	{0:1}
F3	Maximize Material Saving *reference-value-based*	{0:x}
F4	Minimize Utilization *percentage-based*	{0:1}

During the process, the user is given the possibility to define weighting factors to the different objectives given and these weighting factors are applied to the different objective functions F1 - 4. The weighted objective functions are then gathered in a linear equation describing the function for the fitness rating:

$$\mathrm{Q} = \prod \mathrm{Ci} * (\sum \mathrm{ajFj}) \tag{1}$$

Q *Fitness Rating*
C_i *Constraint [0,1]*

F_j	*Fitness indicator*
a_j	*Weighting* ($\sum a_j=1$)

4 Results and Discussion

In order to evaluate the accuracy and validity of the proposed framework and the applied fitness function a proof-of concept is performed based on a pilot project. The chosen pilot project is a real production facility from the food and hygiene sector with a total production area of 5.760m² - Use Case A of the Case-Study. The external dimensions of the hall are 48x120m, with a structural axis grid of 12x24m.The building structure was realised as steel truss-system in primary and secondary direction with truss construction heights of 2,4m. The columns consist of pre-cast concrete cross-sections with dimensions of 60x60cm and the bracing system uses end-fixed columns to bear horizontal loads. Figure 3 shows the 3D Visualisation of the Pilot Project and the applied load-areas in Rhino3D, taking into account snow loads and BSE- and production-related loads.

A variant study is carried out in order to obtain and compare analysis and optimization results. The grasshopper script automatically generates and evaluates numerous design options of the pilot project with the goal of optimization of the structural system. After running the analysis and optimization script, the twelve most relevant design options were categorised according to the structural type and examined in detail. Category 1 contains all options with pure truss structures, options of category 2 contain only girder structures and category 3 options represent a set of mixed structures. A balanced objective weighting (each objective 25% importance) has been defined in the proof-of concept.

- PP: Pilot Project – Truss structure
- Cat. 1: Truss structure - primary & secondary
- Cat. 2: Girder structure - primary & secondary
- Cat. 3: Mixed structure

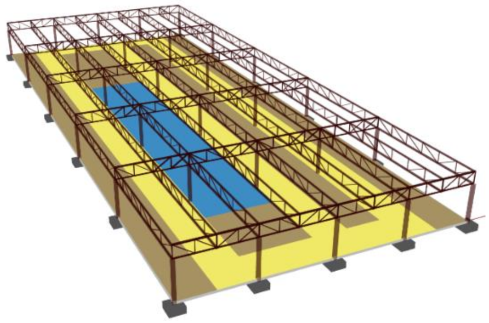

Figure 3. Pilot project model visualisation in Rhino 3D with load distribution.

The optimization results of the best-rated design-option from each category (Cat.1-3) compared to the pilot project (PP) are presented in Table 4.

Table 4. Optimization Results of Proof-of Concept

Options	PP	Cat. 1	Cat. 2	Cat. 3
Variables				
G1 [m]	12	12	12	12
G2 [pc]	4	4	4	4
G3 [m]	24	12	6	12
G4 [pc]	5	10	20	10
G5 [m]	6,35	6,35	6,35	6,35
G6 [m]	9,30	9,30	9,30	9,30
S1 [no.]	1	1	2	1
S2 [no.]	1	1	2	2
Material Demand Results				
steel mass [kg/m²]	45,7	28,7	76,7	89,0
concrete mass [kg/m²]	24,8	25,6	48,9	40,0
Objective Values				
F1	0,94	0,90	0,82	0,90
F2	0,24	0,59	0,59	0,59
F3	1,00	1,27	0,55	0,57
F4	0,91	0,90	0,70	0,76
Fitness Rating				
Q	0,72	0,92	0,67	0,70

Figure 4 presents the best-rated design-option of each category compared to the pilot project in a radar diagram. The objective function of the Material Saving (F3) has a high impact on the performance of the structure.

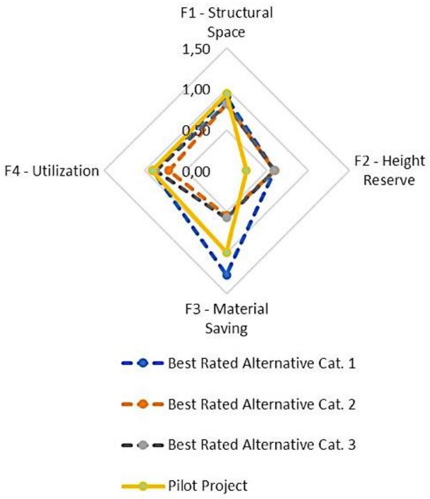

Figure 4. Graphical radar representation of the proof-of concept results.

Table 4 shows that the best rated option with the highest fitness rating is performed by category 1 – the sole truss structure with an axis grid of 12x12m. Highly due to the positive impact of material saving (F3). Results indicate that the Cat. 1 option saves approximately 25% of the structural steel mass compared to the pilot project, mostly because of the axis grid optimization. Additionally, the structural analysis results in cat.1 increase the utilization of the cross-sections compared to the more conservative cross-section selection in the pilot project. This may also be because during the pilot projects design phase, stakeholders probably may have considered additional design parameters and constraints such as structural reserves, which are not yet represented in the framework of the parametric script.

In category 2, the best-rated option still has a high material demand compared to the pilot project and the positive impact of the Height Reserve (F2), due to girder structures, is not able to compensate this drawback. The bad rating of Material Savings (F3) in category 2 shows that the girder structures are hardly competitive to truss structures due to the high BSE loads.

A mixed structure as analysed in category 3 also has a worse performance compared to the pilot project with a fitness rating of Q=0,70.

In conclusion, results of the variant study show that for the applied load scenario truss structures (Cat.1) are more competitive compared to girder (Cat.2) and mixed (Cat.3) structures. An optimization of the pilot projects performance could be obtained by adjustment of the axis grid in x and y direction.

Regarding the evaluation of the fitness function (Q) and the contained objective functions (F1-4), we observe that the determination of the material saving (F3) has a decisive effect on the performance results (see Figure 4) in comparison to other objectives, considering their narrow value range. Further analysis of the mathematical definition of the objective functions is necessary.

Considering the efficiency of the parametric script, the computational time of approximately 10-15 seconds per option on a standard computational system is improvable but legitimate for a complex structural analysis with parallel optimization.

5 Conclusion

This paper proposed a method to support integrated industrial building design exploration with structural optimization, which is crucial to guarantee the long-term flexibility of factories. In a use-case study, ten real industrial construction projects are analyzed in order to define discipline-specific parameters and their interdependencies in industrial building design. The goal is the development of a computational framework integrating discipline-specific data of production planning, architectural-, structural and BSE design in one holistic model. Parametric modeling combined with structural analysis and optimization algorithms for performance-driven design allows the generation, simulation and optimization of different structural layout options for early decision-making in industrial construction projects.

The developed parametric script considers varying primary and secondary axis grid options with different structural types enabling performance improvement of a building's long-term flexibility. A multi-objective fitness function has been developed rating the flexibility of a building structure and serving as multi-criteria decision support model. A proof of concept on a real pilot project, a food production, was conducted in order to validate the efficiency of the process and show the necessity of extending the parametric framework.

In the next step of the research, the parametric script will be further extended according to the lacking parts of the graph data model, integrating missing production and BSE- data. Furthermore, the mathematical background of the current definition and description of the objectives needs to be further investigated. The mathematical definition of the fitness function and its objectives has to be improved and extended with additional objectives in order to define accurate flexibility statements for all stakeholders. Considering the structural analysis and pre-dimensioning results, an in-depth analysis of the used algorithms in Karamba3D is necessary to cope with utilization fluctuations of the generated structures. The proof of concept will be extended by analysing more case-cases, guaranteeing the robustness of the tool in various production scenarios.

Future work will examine and develop methods to integrate the framework of the parametric model into the BIM-based digital platform by bi-directionally coupling it to BIM, Finite-Element-Method Tools and Virtual Reality software, as aimed in the research project BIMFlexi.

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