



Design space exploration for flexibility assessment and decision making support in integrated industrial building design

Julia Reisinger¹ · Maximilian Knoll¹ · Iva Kovacic¹

Received: 18 November 2020 / Revised: 4 March 2021 / Accepted: 4 March 2021 /

Published online: 18 March 2021

© The Author(s) 2021

Abstract

Industrial buildings play a major role in sustainable development, producing and expending a significant amount of resources, energy and waste. Due to product individualization and accelerating technological advances in manufacturing, industrial buildings strive for highly flexible building structures to accommodate constantly evolving production processes. However, common sustainability assessment tools do not respect flexibility metrics and manufacturing and building design processes run sequentially, neglecting discipline-specific interaction, leading to inflexible solutions. In integrated industrial building design (IIBD), incorporating manufacturing and building disciplines simultaneously, design teams are faced with the choice of multiple conflicting criteria and complex design decisions, opening up a huge design space. To address these issues, this paper presents a parametric design process for efficient design space exploration in IIBD. A state-of-the-art survey and multiple case study are conducted to define four novel flexibility metrics and to develop a unified design space, respecting both building and manufacturing requirements. Based on these results, a parametric design process for automated structural optimization and quantitative flexibility assessment is developed, guiding the decision-making process towards increased sustainability. The proposed framework is tested on a pilot-project of a food and hygiene production, evaluating the design space representation and validating the flexibility metrics. Results confirmed the efficiency of the process that an evolutionary multi-objective optimization algorithm can be implemented in future research to enable multidisciplinary design optimization for flexible industrial building solutions.

Keywords Design space exploration · Parametric modeling · Structural performance optimization · Flexibility metrics · Decision making

✉ Julia Reisinger
julia.reisinger@tuwien.ac.at

¹ Department of Integrated Planning and Industrial Building, Institute of Interdisciplinary Construction Process Management, TU Wien, Karlsplatz 13 - E234-02, 1040 Vienna, Austria

1 Introduction

The construction industry is recognized as one of the major natural resources and energy consumers, worldwide consuming 40% of resources and producing 50% of global greenhouse gas emissions (Röck et al. 2018). Within the construction sector, industrial buildings play a critical role in sustainable development as they employ large amounts of resources for foundations, structural systems and the building envelope (San-José Lombera and Garrucho Aprea 2010), producing and expending a significant amount of resources, energy and waste (Heravi et al. 2017). Thus, the need for methods to assess the sustainability of industrial buildings has risen. A variety of tools to assess the environmental impact of buildings exist, such as the environmental system analysis tools (Finnveden and Moberg 2005), green building rating systems (Shan and Hwang 2018) and recycling potential assessment tools (Honic et al. 2019). One of the most common environmental performance assessment methods evaluating industrial buildings is Life Cycle Assessment (Rodrigues et al. 2018; Tulevech et al. 2018).

However, such tools do not consider all necessary sustainability requirements. A resilient building, with the ability to adapt to changes, can increase sustainability. The resilience of a building can be defined as the buildings capacity to adjust easily to natural disasters or changes, such as changes in use and is often dealt with under the concept of flexibility (Marjaba and Chidiac 2016). The concept of flexibility is a prerequisite for extending a buildings life cycle (Cellucci and Sivo 2015), for increasing the reuse potential of a building (Glumac and Islam 2020), and thus can contribute to sustainable development (Gosling et al. 2009). However, existing sustainability assessment tools do not respect the metric of flexibility, though flexibility has become an increasingly important aspect in the design of industrial buildings.

Individualized production, a vast number of product varieties and fast changing technologies result in increased complexity and frequent reconfiguration of manufacturing systems (Huettemann et al. 2016). The concept of changeable and reconfigurable manufacturing infrastructure, supporting new machine deployment and reconfiguration of systems, must be also reflected in the factory buildings (ElMaraghy and Wiendahl 2014). Thus, industrial buildings aim for highly flexible structures in order to allow for rapid adjustments to changing conditions. Flexibility is strongly influenced by the load-bearing structure, as it is the most rigid element with the longest service life in a building. However, structural design considerations usually enter the design process late and are subservient to architectural and manufacturing goals, leading to inflexible floorplans and structures. In order to maximize the flexibility of industrial buildings the focus should be on a coherent planning of building and manufacturing systems and the optimization of the load-bearing structure. However, in current practice production and building design processes run consecutively, lacking in feedback loops and neglecting interactions between discipline-specific designs (Schuh et al. 2011). In Integrated Industrial Building Design (IIBD), which incorporates manufacturing and building criteria simultaneously, multidisciplinary

stakeholders are faced with numerous complex design decisions, involving the choice of multiple conflicting parameter, thus opening up a vast design space. Design space exploration (DSE), referring to the activity of discovering and evaluating design alternatives (Kang et al. 2010) in IIBD is challenging, as interfaces between production and building planning are rarely investigated (Ebade Esfahani et al. 2019) as well as data availability and requirement definitions are missing, declining the quality of final solutions (Kampker et al. 2013). To ensure high flexibility for rapid changes, the factory planning process has to be analyzed in more detail and therefore methods for quantitative evaluation of designs and systematic decision supports are needed (Büscher et al. 2014). Parametric and performance-based design methods are merging that provide design teams to efficiently explore broad design spaces with quick response, leading to well-informed decision-making (Haymaker et al. 2018). However, to effectively apply these methods in IIBD, design teams require a unified framework, merging data from building and manufacturing disciplines.

The definition of flexibility metrics for performance assessment and a clear DSE method for sufficient multidisciplinary decision-support in IIBD, optimizing the flexibility of industrial buildings in relation to changing manufacturing conditions, are the motivation for this paper. Therefore, the main research questions investigated in this paper are:

- (1) What are flexibility metrics in industrial building design, which are respecting manufacturing requirements and how can they be mathematically formulated in order to measure them in a practical way?
- (2) What are the elements representing a feasible design space for IIBD for efficient DSE and decision-making support, avoiding computationally expensive calculations encountered in simulation and optimization later on?

To answer these questions, novel flexibility metrics and a computer understandable design space representation for design exploration in IIBD are developed. Next to this, a parametric design process for DSE with automated structural performance-optimization and quantitative flexibility assessment of industrial buildings is presented. Furthermore, the framework is tested on a real industrial construction project from food- and hygiene production sector. The results of the presented work are important prerequisites for the next steps of the research, in which an evolutionary multi-objective algorithm for multidisciplinary design optimization will be implemented in the parametric process.

The paper is structured as follows: first, the state of the art on flexibility, DSE and decision support tools in building and manufacturing planning through literature review is presented. Second, the applied methodology of an exploratory multiple case study is described. Based on the results the design space representation and formulation of flexibility metrics is shown. The developed parametric framework for DSE in IIBD is tested and the defined flexibility metrics validated on a pilot-case. Finally, the achieved results and directions for future steps are discussed.

2 Literature review

Manufacturing is faced by change, forcing manufacturing companies for permanent adaptation of their factories (Löffler et al. 2012). A need for flexible and adaptable buildings and manufacturing systems to increase sustainability is widely acknowledged in research and industry. In general, flexibility in building design can be defined as the capability of space to functionally or structurally adapt to changes in use to be useful for an extended period (De Paris and Lopes 2018). Several studies identify concepts and criteria of building flexibility. Gosling et al. (2009) developed a building adaptability system model as a way to rationalize flexibility and adaptability in the construction sector. Slaughter (2001) analyses design strategies, significantly increasing building flexibility, presenting three general types of changes which can be expected: changes in the function of the space, changes in the load carried by the systems and changes in the flow of people or environmental forces. The presented design strategies include reduce inter-system interactions, use interchangeable system components, increase layout predictability, improve physical access, enhance system access proximity, simplify partial demolition, improve flow, phase system installation, reduce intra-system interaction and dedicate specific area/volume for system zones. Israelsson (2009) identify the factors material standards, production, planning for future changes and service life, installations, financial aspects and awareness aspects in building flexibility. The majority of the studies investigate flexibility in the design of residential buildings and housing units. De Paris and Lopes (2018) explored housing flexibility through a review of relevant literature, highlighting that a lack of well-defined concepts of flexibility result in the inclusion of different variables in each paper. Cavalliere et al. (2019) propose a BIM (Building Information Modeling)-based parametric model framework for automated flexibility assessment, defining the metrics of housing flexibility as structure modularity, geometrical regularity of plan, location of technical service, removable building elements, percentage/orientation of windows and internal mobile partitions. (Till and Schneider 2006) propose six generic principles for flexible housing: Space (increase capacity and free use of space), construction (structure that allows easy future invention), design for adaption (predicting future scenarios and options), layers of construction, typical plan (generic space without specification) and disposition of technical services (location planning for future changes). Further housing flexibility criteria and strategies are examined by Živković and Jovanović (2012) and Cellucci and Sivo (2015). Housing flexibility in terms of spatial indeterminacy is investigated by Montellano (2015) and Glumac and Islam (2020) present a performance-based framework for housing preferences in adaptive-re-use of office and industrial buildings. A practical instrument to assess the adaptive capacity of buildings is cultivated by Geraedts (2016), identifying a number of flexibility key performance indicators, divided in the layers of site, structure, skin, facilities and space plan. In the category of structure, the flexibility indicators are among others the surplus of the building space and floor, the surplus of free floor height, the surplus of the load-bearing capacity and the positioning of columns or facility zones.

The focus of the above listed research fails to cover specific flexibility aspects in industrial buildings. In industrial building design, the systems flexibility should be defined integrating manufacturing requirements. Manufacturing systems flexibility means being able to reconfigure manufacturing resources in such a way as to produce efficiently different products of acceptable quality. A system's flexibility is necessary to address uncertainties caused by a change in demand, changes in user needs, innovative technology, new regulations or availability of resources (Sethi and Sethi 1990). Manufacturing flexibility has aroused considerable interest among researchers and professionals but also here a comprehensive understanding of the subject remains elusive (Cousens et al. 2009; Kara and Kayis 2004). The most cited authors in literature are Browne et al. (1984), who identified eight dimensions of flexibility and Sethi and Sethi (1990) who extended the classification, adding three more flexibility dimensions. The in total 11 defined manufacturing flexibility dimensions are machine flexibility, operation flexibility, routing flexibility, volume flexibility, expansion flexibility, process flexibility, product flexibility, production flexibility, material handling flexibility, programme flexibility and market flexibility. However, the conducted studies on manufacturing flexibility remain in the realms of operational management and are most closely related with the process technology of manufacturing systems (Beach et al. 2000), objects of the factory building are generally not included in this context. Instead, Wiendahl et al. (2007) introduce the term changeable manufacturing, describing five different types of changeability. Changeability is defined as characteristic to accomplish early and foresighted adjustments of the factory's structures and processes on all levels to change impulses economically, including the factory building. Within this context Wiendahl et al. (2007) describe five so-called transformation enablers that factory planner may use for attaining changeability already in the design phase. The factory transformation enablers are defined as (1) Universality (over-dimensioning and designing objects for diverse functions), (2) Scalability (expansion and shrinkage of factory layout), (3) Modularity (standardized units and elements), (4) Mobility (unimpeded mobility of factory objects) and (5) Compatibility (possible interactions in and outside the factory).

A growing body of literature has investigated the topic of flexibility in both building and manufacturing planning, applying various definitions and concepts. The most common principles of building flexibility are the plan of generic and indeterminate space, regularity of layouts, structural regularity and adaptability, location of technical services, increase of simplicity in systems and materials, designing over capacity and improving the flow through system layouts. However, no conventionally accepted flexibility metrics definition for IIBD incorporating building and manufacturing criteria, have been established. The main aspect of this paper is to define flexibility metrics for IIBD to be integrated into a unique computational framework for quantitative flexibility assessment.

As can be seen from the literature review on flexibility, the load-bearing structure strongly influences the building's and manufacturing's flexibility. However, structural design considerations usually enter the design process late and are subservient to architectural (Mueller 2014) and manufacturing goals (Bejjani et al. 2018), leading to inflexible floorplans and structures. To determine the overall efficiency

of industrial buildings a concurrent assessment of the synergy effects of production processes, technical services and the building itself is needed (Gourlis and Kovacic 2016). Integration is especially crucial for the conceptual design of industrial buildings as decisions made on building and manufacturing flexibility are more impactful when made at the early design stage (Sadafi et al. 2014) (Francalanza et al. 2017). However, major obstacles in interdisciplinary cooperation between building and production planners are due to missing maturity level specifications and missing data management standards (Ebade Esfahani et al. 2019). To achieve integration in the factory planning process a variety of approaches, which are focusing on different specific topics such as the overall project management (Graefenstein et al. 2020) or the managing of interdependencies and information of various tasks (Bejjani et al. 2018; Hawer et al. 2017; Kampker et al. 2013; Schuh et al. 2011) are conducted. However, most of the approaches do not consider the synchronization of manufacturing layout planning and structural design optimization neither do they consider performance improvement regarding flexibility. A sufficient factory information model needs three essential parts: a calculation model, a heterogeneous data integration and decision support tools (Bejjani et al. 2018). Existing factory planning processes neither support a quantitative evaluation of the planning nor assist in holistic and systematic decision support during design (Büscher et al. 2016). Regarding optimization and decision-support tools for industrial facilities, numerous research has been conducted about optimization on product level and manufacturing processes (Büscher et al. 2016; Francalanza et al. 2017; Kluczek 2017), on sustainable manufacturing (Deif 2011) or on manufacturing energy efficiency (Garwood et al. 2018; Mousavi et al. 2016). Usually, less attention is on the integration of industrial building information (Heravi et al. 2015). Thus, several authors propose models concentrating on industrial building level, evaluating the environmental performance through life-cycle assessment (Kovacic et al. 2016; Rodrigues et al. 2018; Tulevech et al. 2018) or analyzing and optimizing energy performance (Bleicher et al. 2014; Gourlis and Kovacic 2016). Critical sustainable development factors in the adaptive re-use of industrial buildings are investigated by Vardopoulos (2019), while San-José Lombera and Garrucho Aprea (2010) study the six scopes of functionality, economy, environment, social and safety within an environmental analysis of industrial buildings. A variety of researcher develop different approaches for multi-criteria decision-making for industrial buildings, such as for sustainability assessment (Heravi et al. 2017) (Cuadrado et al. 2015), for factorial design space exploration studying energy performance, environmental impact and cost effectiveness (Lee et al. 2016) or for space heating system selection (Chinese et al. 2011). Chen et al. (2012) integrate sustainability within the factory planning process and (Lenz et al. 2019) propose a BIM-approach for automatic decision support in factory adaption planning. The University of Hanover (iFA) developed a systematic method evaluating the transformability of a factory based on future requirements, comparing factories by means of benchmarking (Nyhuis et al. 2007). The above listed research are remarkable but focus on either manufacturing modeling or building performance, mostly focusing on energy efficiency. In general, energy performance is optimized in 60% of sustainable building design cases (Evins 2013). However, although early integration of building and manufacturing planning would improve environmental

and economic performance, holistic models that optimize the load-bearing structure towards increased flexibility, receive little attention and fail to fully cover the exploration of the entire design space in industrial construction projects.

In fact, IIBD design teams are faced with numerous complex design decisions and the choice of multiple conflicting criteria, opening up a vast design space. The complexity of sub-discipline models rise to a large combinatorial space of possible solutions, when trying to integrate all specific information, thus design problems are difficult due to the potential combinatorial explosion of the design space (Zdráhal et al. 1996). Decision-making in design entails the process of generating, evaluating, and determining design alternatives to satisfy given requirements or criteria (Lee and Ostwald 2020). Multidisciplinary and contrasting objectives need a pertinent performance information (Méndez Echenagucia et al. 2015), making it advantageous to apply computational design optimization methods (Evins 2013). Parametric design as an exploration and search tool allows the process to navigate the design space efficiently (Motta 1998). Performance-based parametric design operates in the conceptual “design space”, containing all possible alternatives that can be generated by a parametric script, and the “objective space”, covering the designs based on their performance, thus designers get quick feedback about how different alternatives behave and get guidance for decision-making (Brown et al. 2020). Parametric and performance-based design tools in building design have been widely employed by authors in architectural and structural design domain, focusing on design space exploration and structural optimization of sub-systems (Brown et al. 2020; Brown and Mueller 2016; Makris et al. 2013; Mueller and Ochsendorf 2015; Pan et al. 2020; Turrin et al. 2011). In this general approach, a parametric design process shows remarkable potential to support optimization and decision making in IIBD. Thus, to achieve integration several architectural, structural, technical service and manufacturing aspects and their interdependencies need to be considered and a customized workflow on the specificities of industrial buildings developed.

However, an essential problem of any performance optimization is concrete parameter definition and the handling of computational time (Baril et al. 2012; Emmerich and Deutz 2018) as optimization methods coupled with building simulation programs need enormous processing resources (Machairas et al. 2014). A non-well defined design space runs the risk of including physically and/or geometrically unnecessary search regions, wasting search time (Sóbester and Powell 2013). A large pool of possible designs need an efficient exploration scheme to provide sufficient feedback (Kontogiannis and Savill 2020).

In this work the development of a concrete design space for IIBD is proposed to reduce the number of design options in the search, thus to consider fast and feasible results during multi-objective optimization, which will be implemented in the next steps of the research to enable multidisciplinary design optimization.

The state of the art analysis reveals some limitations that hinder an early integration of building and manufacturing system planning and efficient flexibility assessment in industrial building design. First, there is a lack of a novel definition of flexibility assessment metrics, respecting both manufacturing systems and industrial building criteria. In addition, there is a lack of multidisciplinary design optimization processes specifically customized for the integration of manufacturing layout

planning and structural performance optimization in industrial building design. To overcome these limitations, this paper proposes a novel design process based on parametric modeling, performance-based structural optimization and numeric flexibility assessment for IIBD. In this light, a parametric model framework for DSE in IIBD is developed, automatically optimizing the structural system towards maximum flexibility, thus to reduce the environmental and economic impact of industrial buildings in long-term. Such a process facilitates multidisciplinary designers a holistic decision-support tool, providing diverse types of flexible, thus sustainable industrial building design alternatives.

3 Research methodology

The purpose of the research is the definition of novel flexibility metrics, respecting both building and manufacturing requirements. Furthermore, to construct a feasible design space for IIBD, holistic data from building design including architectural, structural, technical service and manufacturing planning are collected and the interdependencies analyzed. Results of the state-of-the-art analysis and the multiple case-study methodology are combined in a unified design space representation for IIBD. The defined design space is then translated into a parametric model framework, enabling automated optimization of the building structure and quantitative flexibility assessment of industrial buildings in real-time, supporting multidisciplinary design teams in systematic DSE and decision-making. The parametric model, thus the design space representation, is tested on a pilot-project of a food-and hygiene production facility and the flexibility metrics validated. Figure 1 gives an overview of the research methodology and the research outputs of the study.

3.1 Exploratory multiple case study

In order to gain an in-depth understanding of a complex real phenomenon and to understand the differences and similarities between different cases an exploratory multiple case study is carried out according to Yin (2009). A total number of 29 real industrial building projects represent the use-cases, which are representative for the research objective (Eisenhardt 1989). Due to different types of productions 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 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 (Eisenhardt and Graebner 2007). To increase the reliability and validity of the research findings multiple sources of evidence should be used for data collection (Yin 2009). Therefore, the case study investigated the following sources to collect holistic data: (1) Expert interviews and (2) Use-case study of documents and archival records. The data obtained from the case study was supplemented with the

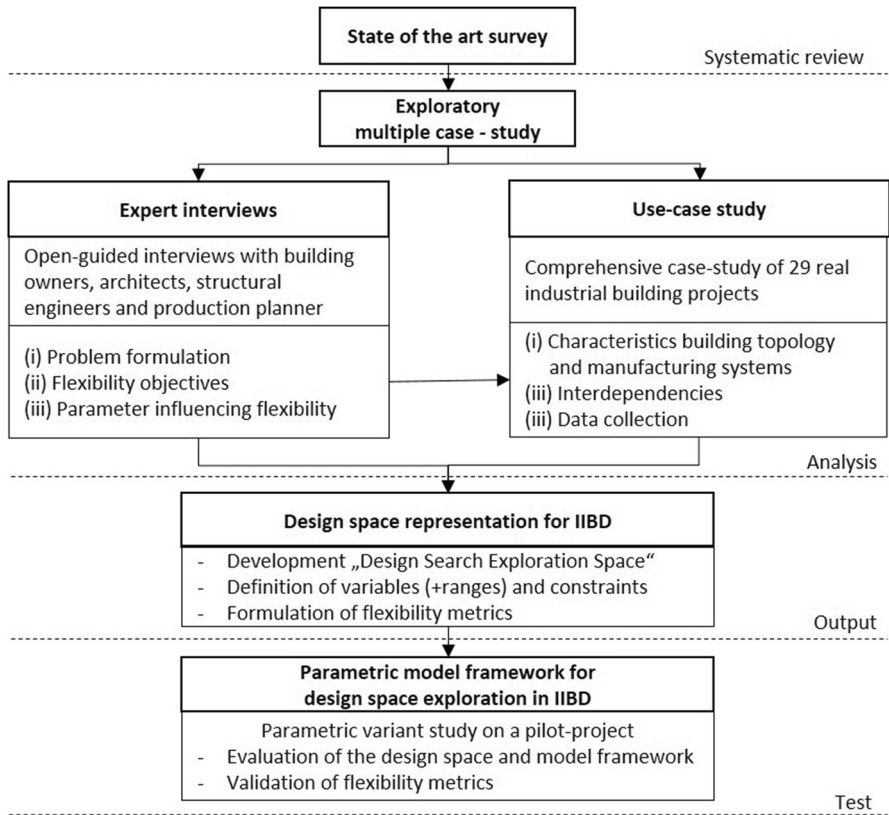


Fig. 1 Overview of the research methodology and scope of paper

data collected in the state-of-the-art survey. Thus, a triangulation of complete data sources could be achieved. Table 1 gives an overview of the examined use-cases.

3.1.1 Expert interviews

The conducted expert interviews allowed the mapping of discipline-specific knowledge and needs and requirements regarding flexibility in IIBD. Thereby, fifteen experts (five building owners, three architects, three structural engineers and four production planners) involved in the construction of five use-cases of the case study where interviewed via guided, open-ended interviews. The obtained information facilitated the definition of flexibility goals and concrete flexibility metrics and associated parameter in IIBD. The evaluation of the interviews was conducted according to the following methodology: After the transcription of the interviews, a list of all relevant statements was compiled, allowing categorization of the statements into three categories: Objectives (Metrics), design processes and parameter in IIBD. The interviews were particularly useful as they provided a direct insight into what

parameter and how they influence the flexibility of industrial buildings. Table 2 provides an overview of the expert interviews conducted.

3.1.2 Use-case study

In the use-case study, documentations and archival records were investigated to gain a deep insight into the characteristics of industrial building topologies and

Table 1 Use-cases of the case study, analyzing 29 representative real industrial building projects

Use-Case	Area [m ²]	Primary structure type
1—Automotive		
1A	12 100	Steel framework
1B	20 700	Space framework steel
1C	160 700	Steel framework
2—Food and hygiene		
2A	5 760	Steel framework
2B	700	Saddle roof timber girder
2C	4 800	In-Situ RC Concrete
2D	1 880	Timber GLT girder
2E	2 730	Timber framework
2F	1 110	Timber GLT girder
3—Logistics		
3A	8060	Saddle roof timber girder
3B	5040	Steel profile girder
3C	5000	Precast concrete girder
3E	30,000	Timber GLT girder
3F	37,500	Precast concrete girder
3G	2500	Steel profile girder
4—Metal processing		
4A	2 800	Steel profile girder
4B	28 220	Precast concrete girder
4C	16 200	Timber framework
4D	6 000	Steel framework
4E	7 200	Steel framework
4F	15 600	Timber GLT girder
4G	7 200	Saddle roof timber girder
4H	14 500	Timber framework
4I	4 000	Suspended GLT girder
4J	14 500	Precast concrete girder
4K	6 600	Timber framework
5—Special		
5A	2 800	Suspended GLT girder
5B	2 850	Precast concrete girder
5C	60 000	Steel framework

manufacturing system structures. The documents and records analyzed were: (1) Discipline-specific drawings from architectural, structural, technical service and manufacturing planning, involving floor plans, sections, details and production layout plans. (2) Digital design models and (3) Technical project reports. Functional and technical interdependencies between the discipline-specific objects were analyzed and concrete data values and ranges for building- and production-specific variables and constraints defined. For each use-case, the results were structured and cross-sectional checked in order to identify structural and functional commonalities. This enabled the categorization and definition of common supporting structures, materials, column axis grids, and load conditions encountered in industrial building design. The collected data served for the development of the design space and the parametric model framework.

3.2 Design space representation and parametric model development

The methodology for the design space representation and parametric model framework developed in this study, followed the “Design Space Construction Framework” approach and the design space theory terminology from Haymaker et al. (2018), see Table 3. A precise design space was build based on the case study results, giving the possibility to find flexible industrial building solutions within reasonable calculation time. Therefore, the flexible industrial building problem was encoded a structure of variables and vectors, parametrically describing the design search space. Furthermore, to discover feasible solutions and to guarantee a focused search later on, constraints were defined. To enable a flexibility measure, which is a formula, algorithm or methodology to generate a value for a given flexibility type under given conditions (Shewchuk and Moodie 1998) the obtained flexibility goals from the interviews are mathematically formulated into metrics based on the defined decision variables.

3.3 Parametric model framework description for design space exploration

The design space representation is translated into a parametrical model framework for DSE with automated structural optimization and quantitative flexibility assessment. The parametric design process is developed in the visual programming tool

Table 2 Overview of the conducted expert interviews within the case study

Expert interviews	Use-Case 2A	Use-Case 2C	Use-Case 4C	Use-Case 4 K	Use-Case 5C
Building owner	1	1	1	1	1
Architect	0	1	1	1	0
Structural engineer	1	1	0	1	0
Production planner	1	1	1	1	0

Table 3 Terminology for design space theory used in this study according to (Haymaker et al. 2018)

Terminology in design space theory (Haymaker et al. 2018)	
Objectives/Goals	Objectives are specific targets to achieve and Goals represent specific ecological or economic targets, defined by the stakeholders.
Constraint	represent the admissible limit of an input <i>variable</i> or outcome and must be satisfied for an <i>alternative</i> to be valid
Metrics	The definition of <i>metrics</i> allows the verification of the fulfillment of the <i>constraints</i> and the evaluation of the degree of fulfillment of the objectives
Design alternatives	are the explored potential solutions to a given design problem, while each <i>alternative</i> corresponds to a particular set of options for every variable of the problem
Variables	can be discreet or continuous input parameter within a <i>range</i> that constrain all possible states of such a <i>variable</i> between lower and upper bounds.

Grasshopper for Rhino3D (Preisinger and Heimrath 2014), enabling geometric representation and automation of the design alternative generation. Additionally, the Grasshopper component Karamba3D, allowing early-stage structural analysis, form-finding and structural optimization, is used for the structural performance optimization. The flexibility assessment is done in the context of the parametric modeling environment because they are computationally trivial. The assessment results and the associated parameters for every design alternative are then exported to a excel database for data visualization and alternative comparison, which sorts the data and results from each design alternative and facilitates the exploration of trade-offs across the flexibility metrics for decision-making support.

The parametric model framework consists of seven discrete steps (see Fig. 2):

(1) Input layout—assembly of “Production Cubes”, (2) Input structural—“Structural system grid” and loads, (3) Automated generation of geometry, (4) Definition of structural elements (5) Structural analysis, (6) Structural performance & positioning, (7) Results assessing the flexibility and net costs.

4 Design space representation

This chapter presents the design space development for flexible building industrial building structures. The design space representation for IIBD is developed for parametric DSE to find satisfying building solutions within reasonable calculation time and to support in decision-making. By narrowing the design space, the developed multi-objective optimization algorithm, which will be developed and implemented in future research, can be focused on optimization, instead of having to explore every possible alternative. The proposed design space representation consists of three key components to facilitate efficient design exploration in IIBD: (1) definition of variables for design search space exploration, (2) the formulation of constraints and (3) definition and derivation of four flexibility metrics.

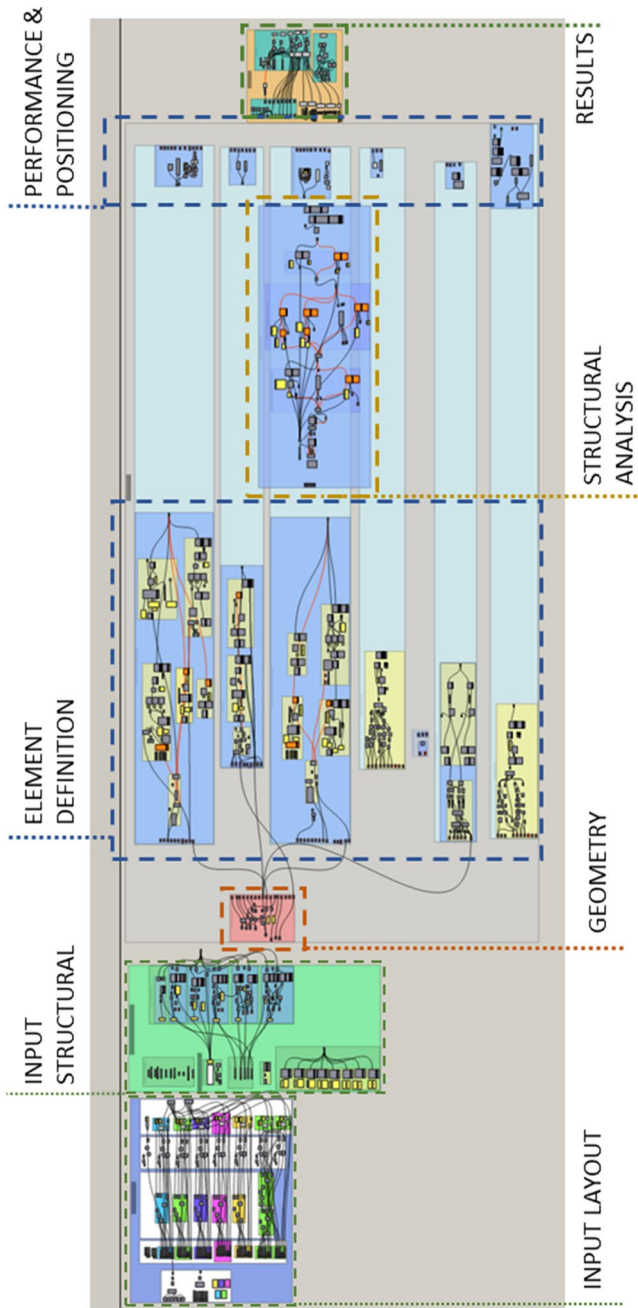


Fig. 2 The developed parametric model framework in Grasshopper for Rhino3D. To test the feasibility of the design space and to validate the flexibility metrics a variant study on a pilot use case from the food-and hygiene production sector is conducted at the end of the study

4.1 Design search space exploration

A “structural system grid” is suggested to describe a flexible industrial building structure by means of the design search space representation. Figure 3 displays the structural system grid with production cubes assembly for an example industrial building. The structural system grid describes the main dimensions and structural elements of the building and is defined by three vectors and three structural element types: $H\{f_i, g_j, h_k, r_i, s_j, t_{ij}\}$. Here, f_i, g_j, h_k describe the continuous dimensioning of the industrial building grid with indices i, j , and k . Following this, i is the x -, j is the y - and k is the z - index of the grid. The variables r_i, s_j and t_{ij} are discrete integer and describe the structural element type within the grid axis. Five different structural types can be assigned to the primary grid in x -direction (r_i =primary load-bearing structure), four types to the secondary grid in y - direction (s_j =secondary load-bearing structure) and two structural types can be assigned to the z -direction (t_{ij} =columns). The entire structural system grid is used to perform design modifications; therefore the complete design search space is described by the vectors and variables: $f_i, g_j, h_k, r_i, s_j, t_{ij}$. The rectangle region, which results from the outer dimensions of the industrial building, is defined as R . The maximum building gross floor area of the building rectangle is A_R . The variables used are described in the Eqs. (1, 2, 3, 4).

$$f_i \geq 0, i \in \{1, 2, \dots, N_f\} \tag{1}$$

$$g_j \geq 0, j \in \{1, 2, \dots, N_g\} \tag{2}$$

$$h_k \geq 0, k = 1 \tag{3}$$

$$A_R = \sum_{i=1}^{N_f} \sum_{j=1}^{N_g} a_{i,j} = \sum_{i=1}^{N_f} \sum_{j=1}^{N_g} |\vec{f}_i \times \vec{g}_j| \tag{4}$$

r_f = (Steel framework, Steel profile, T-Beam precast concrete, GLT girder, Timber framework).

s_g = (Steel framework, Steel profile, T-Beam precast concrete, GLT girder,)

t_{ij} = (Precast concrete-quadratic, Steel-HEM-profile).

In order to be able to consider production planning in the design search of the structural building topology, the production process is considered in the study. A production type can be divided into three main processes: procurement, production/assembly and distribution. Each main process can be further divided into sub-processes, such as storage, conveying, milling, etc. Each sub-process results in the arrangement of so-called "production cubes". One production cube is defined by three variables: $C_p\{a_p, b_p, c_p\}$, where a_p is the cube dimension in i - direction, b_p is the cube dimension in j - direction, c_p is the cube dimension in k - direction and p the total number of cubes within the production layout. The rectangle, which results

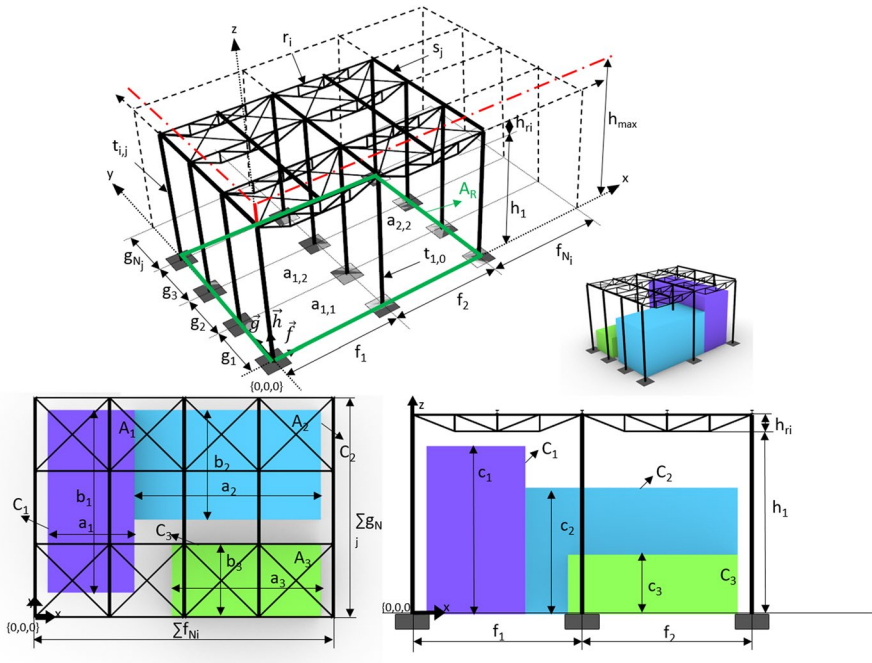


Fig. 3 The industrial building is described by grid vectors f_i, g_j, h_k and grid element variables $r_i, s_j, t_{i,j}$ while the production layout contains production cubes C_p described by the variables a_p, b_p, c_p

from the outer dimensions of one production cube C_p , is defined as R_p . The total production area layout is the sum of the area of all production cube rectangles and is defined by A_p . The arrangement of the production cubes is set as a constraint during optimization, as individual production cubes may not overlap and no production area may exceed the hall area. Equation 5 and 6 describe the variables used, describing the production cubes, thus the sum of all production cubed represents the production layout:

$$a_p, b_p, c_p, R_p \geq 0, p \in \{1, 2, \dots, m\} \tag{5}$$

$$A_p = \sum_{p=1}^m \text{area of } R_p = \sum_{p=1}^m (a_p \cdot b_p) \tag{6}$$

The list of variables considered as input parameters for the industrial building structure is given in Table 4. The design variables are defined as the position of the columns, representing the axis grid in x - and y - direction (f_p, g_p, N_f and N_g). Furthermore, an important grid variable represents the z -direction for flexible hall height adjustments (h_k). The primary and secondary structure type depend on the material and structural system and can be chosen variable in a range of pre-defined systems (r_p, s_j and $t_{i,j}$). The bracing system of walls and roof (b_x) can be chosen within seven options. A load case describing the future retrofitting ability of the system (F_{RT}) is

defined, which is variable between zero (no future retrofitting) to 2 kN/m² (high additional loads).

The list of variables considered as input parameters for production planning, describing the production layout via production cubes assembly, is given in Table 5. Inputs of a_p , b_p , and c_p dimension in x , y and z direction of the machine itself, the work area around the machine and the maintenance area, result in the entire production cube description C_p . A production cube contains dimensions and loads from the machines itself, the workspace around the machine and the maintenance area. Furthermore, loads and required media supply for the given areas are defined to be respected in the DSE.

4.2 Constraints

To be a practical application and to discover feasible design solutions in the search, constraints have to be handled. Table 6 shows the set of constraints as well as the rules involved. $X = \{x_1, x_2, \dots, x_n\}$: covers the set of constraints, limiting the previously defined variables for ensuring a consistent design solution, whereby n is equal to nine. On the first hand, the industrial building system will be evaluated against structural stability constraints such as (x_1) stress utilization, (x_2) displacement, (x_3) structural system's stability and (x_4) span width of tertiary system. On the other hand, the constraints which are subject to building dimension restrictions are (x_5) maximum building height on the property, (x_6) positioning of production cubes, (x_7) production layout size, (x_8) property size and (x_9) the at most planned costs, described in the Eqs. (7 – 16).

Constraint x_1 : The actual stress utilization (σ) in the load-bearing elements must not exceed the maximum utilization (σ_{max})

$$\sigma_{r_i, s_j, t_{i,j}} \leq \sigma_{r_i, s_j, t_{i,j}}^{max} \tag{7}$$

$$j = 1, \dots, N_g \tag{8}$$

$$i = 1, \dots, N_f \tag{9}$$

Constraint x_2 : maximum allowable displacement (δ) of primary and secondary structure must not be exceeded:

$$\delta_{r_i, s_j} \leq \delta_a = l/300 \tag{10}$$

Constraint x_3 : stability of $H\{f_i, g_j, h_k, r_i, s_j, t_{i,j}\}$ must be internal and external true=0; false=1.

Constraint x_4 : The secondary axis grid must be smaller than the tertiary span width of the roof construction, which is constrained with a maximum length of 6 m:

$$|\overrightarrow{g_j}| \leq 6m \tag{11}$$

Table 4 Variables for flexible industrial building design presented in the design space for IIBD

Variables (input parameter)			Constraints			
Variable	Type	Property	Unit	Min.	Max. Options	
Horizontal and Vertical Modularity Grid [x, y, z]						
f_i	Primary Axis Grid (x-)	continuous/constrained	Input/ user modifiable	m	6	42
g_j	Secondary Axis Grid (y-)	continuous/constrained	Input/ user modifiable	m	6	24
N_f	Primary Axis fields	continuous/constrained	Input/ user modifiable	pc	1	8
N_g	Secondary Axis fields	continuous/constrained	Input/ user modifiable	pc	1	8
h_k	Inner Hall Height (z-)	Continuous	Input/ user modifiable	m	$h_k \leq$ maximum. building height—construction height	14
Load-Bearing Structure Type						
s_j	Secondary Load-Bearing System	discrete/ integer valued	Input/ calculated	-	Steel Framework, Steel Profile, T- Beam Precast Concrete, GLT Girder	4
r_i	Primary Load-Bearing System	discrete/ integer valued	Input/ calculated	-	Steel Framework, Steel Profile, T-Beam Precast Concrete, GLT Girder, Timber Framework	5
Column Type						
t_{ij}	Construction Material Columns	discrete/ integer valued	Input/ calculated	-	Reinforced Concrete Quadratic, Steel HEM	2
Bracing Type						
b_x	Bracing Wall and Roof	discrete/ integer valued	Input/ user modifiable	-	1Y, 2Y, 1X, 2X, 1X1Y, 2X2Y, None	7
Load Case						
F_{RT}	Retrofitting Load	continuous/ constrained	Input/ user modifiable	kN/m ²	0	2
						3

Table 5 Information stored in a production cube in the design space for IIBD. The production process layout R_p is described as the sum of all production cubes C_p

a_p	b_p	c_p	A_p	C_p	Loads	Media Supply
Production Cube of a sub-process						
Machine dimensions						Compressed Air
[m]	[m]	[m]	[m ²]	[m ³]	[kN/m ²]	Gas
Workspace area						Air Supply
[m]	[m]	[m]	[m ²]	[m ³]	[kN/m ²]	Sprinkler
Maintenance area						...
[m]	[m]	[m]	[m ²]	[m ³]	[kN/m ²]	...

Constraint x_5 : The maximum building height of the property (h_{max}) must be respected and the outer dimensional height of the building, including the height of the roof construction (h_{roof}) must be smaller than h_{max} :

$$(h_k + h_{ri} + h_{sj} + h_{roof}) \leq h_{max} \tag{12}$$

Constraint x_6 : The individual production cube boundaries (R_q, R_r) must not overlap with each other:

$$R_q^\circ \cap R_r^\circ = \emptyset \text{ for } q \neq r \text{ and } q, r = \{1, 2, \dots, m\} \tag{13}$$

where R° denotes the interior rectangle.

Constraint x_7 : The maximum production layout boundary (R_p), which results from the external limits of the individual production cube boundaries (R_q, R_r) must not exceed the rectangular boundary (R) of the industrial building itself:

$$\bigcup_{p=1}^m R_p \subseteq R \tag{14}$$

Constraint x_8 : The industrial building boundary (R) must fit in the property boundaries (R_{prop}):

Table 6 Set of constraints in the design space for IIBD

Constraints		
X	Description	Possible values
×1	Stress utilization of load-bearing elements ≤ 1.0	[0,1]
×2	Structural displacement \leq allowable displacement	[0, x]
×3	Stability of structural system must be given	0 = true; 1 = false
×4	Secondary axis grid < span width of tertiary system	[0,6]
×5	Industrial building height \leq maximum building height	[0,1]
×6	Production cubes must not overlap with each other	[0,1]
×7	Building dimension > production layout	[0,1]
×8	Building dimension < property dimension	[0,1]
×8	30% of the initial planned building costs may be exceeded	[0,1]

$$R \subseteq R_{Prop} \quad (15)$$

Constraint x_9 : At most 30% of the initial planned costs for the building (ϵ_{max}) may be exceeded from the actual costs of the design option (ϵ_H):

$$\epsilon_{max} \cdot 1.30 \leq \epsilon_H \quad (16)$$

4.3 Flexibility Metrics

In the proposed research, we define flexibility “as the ability of the building structure to resist and adapt to changes in use through changing manufacturing conditions”. The flexibility metrics developed in this work rely on a combination of the expert interview results and the flexibility and changeability criteria proposed in (Cavalliere et al. 2019; Geraedts 2016; Wiendahl et al. 2007) since these authors have attempted to provide flexibility definitions relevant for the focus of this study.

The evaluation of the interviews revealed that the most important goals for flexible industrial buildings are the following: (1) maximizing the load-bearing capacity for future retrofitting of energy media supply, (2) unimpeded expandability of the production layout area during full operation, (3) maximum free hall height and (4) maximum free gross floor area. These findings are also in line with the findings from the state of the art analysis on flexibility presented in chapter 2. Therefore, the flexibility metrics defined in the study and respected in the design space for IIB are the following: (O4) maximize the load-bearing capacity for retrofitting, (O5) maximize the expandability of the production layout, (O6) maximize the hall height reserve and (O7) minimize the amount of columns standing inside the production area. Table 7 describes the four flexibility metrics for IIBD and its definitions.

The flexibility metric O4 aims to maximize the carrying load of the load-bearing structure, by respecting increased forces for retrofitting purposes. F_{RT} is the decision variable for the applied retrofitting load. The rating is 1 if the highest possible value of the retrofitting value is selected ($F_{RT,max}$) and the rating is lower the smaller the applied value of F_{RT} is. When no retrofitting load is applied, the rating is zero.

$$RF = \frac{F_{RT}}{F_{RT,max}} \quad (17)$$

The definition of the flexibility metrics O5-O7 is partly based on calculation methods presented in (Cavalliere et al. (2019)), presenting distance-based indicators (DIST), based on the distance between points, and percentage-based indicators (PERC), based on percentage ratio between areas. A PERC-based indicator is used for the calculation of the flexibility metric O5 in order to maximize the expandability of the production area for future expansion, defined by A_{FS} . It is beneficial if there are still free, undeveloped areas of A_{FS} left in the industrial building for future expansion of the production layout. The indicator is calculated by the inverted ratio of production layout area (A_p) to building area (A_R), rating bad solutions ($A_p = A_R$) with 0 and the best option ($A_p = 0$) with 1:

$$\text{PERC.A}_{FS} = 1 - \frac{A_p}{A_R} \text{ where } A_p = \sum_{p=1}^m (a_p \cdot b_p) \quad (18)$$

The DIST-based indicator serves for definition of the flexibility metric O6, maximizing the building height reserve inside the industrial building (h_r), allowing later changes in production and use, requiring more height. In order to reach the goal of maximum height reserve the DIST-based fitness function must be minimized. Thereby the available height reserve, which results from the maximum building height (h_{max}) minus the highest production cube ($c_{p,max}$) and the construction height of the load-bearing structure ($h_{ri} + h_{sj}$), is in ratio with the maximum height available for the structural system ($h_{max} - c_{p,max}$).

$$\text{DIST.h}_r = \frac{(h_{max} - c_{p,max} - h_{ri} - h_{sj})}{(h_{max} - c_{p,max})} \quad (19)$$

Finally, the flexibility metric O7 aims to maximize the flexibility within the floor plan to enable unlimited production process changes with as few columns as possible standing inside the production area. The objective rating is based on the available axis grid choices (f_i and g_i). The smallest possible grid ($f_{i,min}$ and $g_{i,min}$) has the rating 0 and the largest grid dimensions ($f_{i,max}$ and $g_{i,max}$) has the rating 1.

$$\text{PERC.A}_G = \frac{f_i \cdot g_j}{f_{i,max} \cdot g_{j,max}} \quad (20)$$

5 Test case: parametric model framework

This section presents the test case to demonstrate the suitability of the design space representation, to evaluate the parametric design process and to validate the flexibility metrics. The selected pilot project is a real food- and hygiene production facility, representing use-case 2A of the case study, with a total production area of 5 760 m². The external dimensions of the production hall are 48 m × 120 m, with a structural axis grid of 12 m × 24 m. The structural type consists of a steel truss framework system in primary and secondary direction with truss construction heights of 2.4 m. The columns consist of pre-cast concrete cross-sections with square dimension of 60 cm, using a bracing system with end-fixed columns to bear horizontal loads.

5.1 Variant study

A variant study is carried out to obtain and analyze the performance results. The set of decision variables, constraints and flexibility assessment metrics considered in the parametric framework are those of the design space representation for IIBD, presented in chapter 4. Next to the previously presented flexibility metrics, the net production cost of the structural system are assessed. In the study, a balanced weighting

Table 7 Overview over the flexibility assessment metrics defined for flexible IIBD

<i>Flexibility assessment metrics in IIBD</i>			
Key Indicator	Goal		
O4	Retrofittability		
O5	Expandability		
O6	Flexibility in space		
O7	Flexibility in floor plan		
Performance Indicator	Scenario/ Parameter	Metric	Evaluation Method
Retrofitting Load RF	Retrofitting Load	% (N/mm ²)	F_{RT} -ratio
Floor space reserve A_{FS}	Unused Floor Area	% (m ²)	PERC-based
Height reserve Hr	Unused height	% (m)	DIST-based
Axis Grid dimension Ag	Axis Grid	% (m ²)	PERC-based

of the flexibility metrics has been defined, whereby all goals are equally worth 25% in order to be able to be validated and comparable at the end.

Within the variant study, nine different axis grid combinations are defined and examined. The considered axis grid combinations are presented in Table 8.

The possible design alternatives are categorized according to the following six structural types, whereby each axis grid combination is assigned to each structural type alternative, resulting in 54 design alternatives: (C) Concrete girder, (SF) Steel-framework, (SP) Steel profile, (TG) Timber GLT girder, (TF) Timber framework and (SM) Steel mixed. SM represents a set of mixed steel structures with steel frameworks in primary and steel profiles in secondary direction. Furthermore, all possible design alternatives are calculated first with fixed columns (b_x =Bracing Type 0) and second with hinged columns+bracing ($b_x=6$), resulting in a total number of 108 examined design alternatives. Each design combination is calculated with a retrofitting load of $F_{RT}=1.0$ kN/m². In order to respect different retrofitting loads to test the flexibility metric O4, the design combinations of b_x =Type 0 are additionally evaluated with no retrofitting load applied, resulting in a total number of 162 design alternatives examined in the variant study.

5.2 Results and discussion

The parametric model automatically evaluates all 162 design alternatives, giving feedback to the flexibility rating and the resulting net cost of the structural systems of the industrial building. Figure 4 shows the results of the variant study, presenting the lowest cost alternatives and the most flexible alternatives.

Table 9 presents the most flexible alternatives examined within the solution space, consisting of variable constellations, where the hall dimensions are 120 m × 48 m, the retrofitting load is 1.00 kN/m² and the bracing type=0. The flexibility rating can be further increased, by increasing the hall dimensions, as seen in the O5 variation presented at the end of Table 9. O5 is calculated by the inverted ratio of available production area to available total building area. Since the production layout remains the same, but the building area increases, the expandability rating improves. The alternatives presented in Table 10 are the alternatives with the lowest cost examined within the solution space, representing variable constellations of hall dimensions of 120 m × 48 m, a retrofitting load F_{RT} of 1.00 kN/m² and the bracing type $b_x=0$. Costs can be further decreased by applying no retrofitting load, as can be seen in variant O4 at the end of. The lowest cost alternatives are those with axis grids of 12 m • 6 m, representing the smallest possible grid size in the rating scale. Due to this, the flexibility rating of O7 is zero. Smaller grids mean smaller span width, thus decreased element dimensions.

Figure 5 visualizes the most flexible alternative and the lowest cost alternative, including the production layout in the parametric modeling tool Rhino3D.

SM types perform the highest flexibility (>0.5) but are also the ones with the highest costs. Whereas a SF system has an equal flexibility rating with much lower costs. The cheapest design alternatives are structures of TG, but the flexibility rating does not perform as well as the SF and SM options. This result can

Table 8 Axis grid combinations examined in the parametric design process for DSE

Grid Combinations	1	2	3	4	5	6	7	8	9
f_i Primary Axis Grid (x-)	12	12	12	16	16	16	24	24	24
g_j Secondary Axis Grid (y-)	6	12	20	6	12	20	6	12	20

be justified, as the TG structures require more column supports in the production area, as their span width capacity is lower than those of trusses. TF are amongst the lower cost alternatives but do not perform well in the flexibility rating. C are in the upper range according flexibility but typically involve high costs. The system with the highest flexibility is the steel framework option SF-9-1 with costs of 1 157 000 € and a flexibility rating of 0.56 and an axis grid of 24 m × 20 m. The lowest cost alternative is the timber girder option TG-1-1 with costs of 546 000 €, a flexibility rating of 0.46 and an axis grid of 12 m × 6 m, highly limiting the flexibility in floor space.

Results of the impact analysis of the flexibility metrics on the net costs is presented in Fig. 6. The impact of O4 is shown in Fig. 6a O4 indicates the durability of the supporting structure, evaluating the possibility of adding a retrofitting load for future increased loads in case of production changes. The first variant is adding a retrofitting load of 1.0 kN/m² and in the second variant, no retrofitting load is applied, decreasing the flexibility of the system. The costs increase 8% when a retrofitting load is applied because bigger element dimensions are needed. SF options increase costs by an average of 11%, whereas SP options have a cost increase of 5%. TG and TF have the least net cost of all structural systems, but have a strong increase of the cross-section dimensions, thus costs, when additional loads are applied. The TG show a cost difference of 18% and the TF even 35%. The SM structure costs increase 13%, when a retrofitting load is applied.

The cost impact of O5 can be seen in Fig. 6b, evaluating the expandability of the production system. In evaluation, the production area stays the same, but the building area is increased to a hall size of 140 m × 48 m. Due to the fact, that the ratio production area to building area is calculated, the resulting cost difference of 14% is the same for every variant. O5 does not have a direct impact to structural system itself, but on the architectural layout design.

Figure 6c presents the impact of O6, representing the flexibility in space, which is calculated by the height factor *DIST.hr*. Increasing *DIST.hr* has a very small effect on the costs, which can be seen in the very flat resultant. This is valid as the height does not change the dimensioning of the primary and secondary structure. It only has an influence on the column design. However, O6 has a major impact on the flexibility rating itself, as it directly evaluates the height of the supporting structure.

Finally, Fig. 6d presents the cost impact of O7, evaluating the flexibility of the floor plan, calculated by the indicator *PERC.A_c*. The resultant of *PERC.A_c* is quite steep, having a high impact on the net costs, thus on the material demand of the structural system. O7 has a quadratic influence as it evaluates the area of the axis grid. This quadratic influence, in which larger axis grids are evaluated much

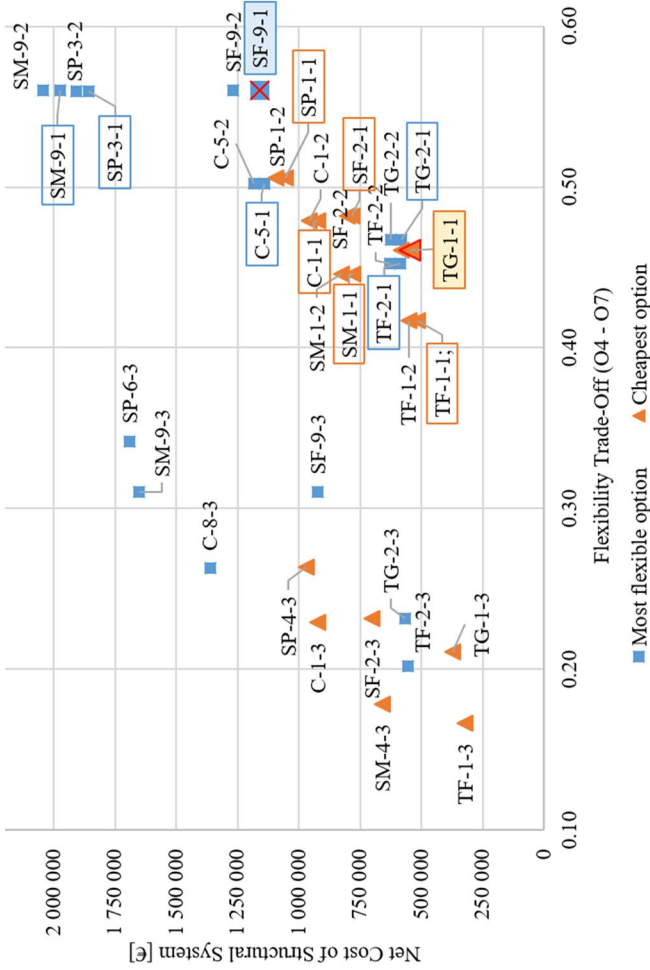


Fig. 4 shows the most flexible and lowest cost alternatives examined in the design space

Table 9 Representation of the most flexible alternatives, when the hall dimensions are 120 m × 48 m, the retrofiting load = 1.0 kN/m² and bracing type = 0 and the variant by increased hall size

Most flexible alternatives ($A_r = 120 \text{ m} \times 48 \text{ m} = 5\,760 \text{ m}^2$, $F_{RF} = 1.0 \text{ kN/m}^2$, bracing type 0)						
Structural Type	C	SF	SP	TG	TF	SM
Best flexibility performance	C 5–1	SF 9–1	SP 3–1	TG 2–1	TF 2–1	SM 9–1
f_i —Primary Axis Grid [m]	16	24	12	12	12	24
N_f —Primary Axis Fields	3	2	4	4	4	2
g_j —Secondary Axis Grid [m]	12	20	20	12	12	20
N_g —Secondary Axis Fields	10	6	6	10	10	6
Net Costs [in k €]	1 140	1 157	1 856	583	584	1 974
O4—Retrofittability	1.00	1.00	1.00	1.00	1.00	1.00
O5—Expandability	0.14	0.14	0.14	0.14	0.14	0.14
O6—Flexibility in space	0.63	0.29	0.77	0.59	0.53	0.29
O7—Flexibility in floor plan	0.24	0.81	0.33	0.14	0.14	0.81
Flexibility Rating	0.50	0.56	0.56	0.47	0.45	0.56
<i>O5 Increased hall Size</i>						
$A_r = 140 \text{ m} \cdot 48 \text{ m} = 6\,720 \text{ m}^2$	0.26	0.26	0.26	0.26	0.26	0.26
Flexibility Rating	0.53	0.59	0.59	0.50	0.48	0.59

Table 10 Representation of the lowest cost alternatives with hall dimensions of 120 m × 48 m, retrofiting load = 1.0 kN/m² and bracing type = 0 and a variant, with no retrofiting load

Lowest cost alternatives ($A_r = 120 \text{ m} \times 48 \text{ m} = 5\,760 \text{ m}^2$ and $F_{RF} = 1.0 \text{ kN/m}^2$, bracing type 0)						
Structural type	C	SF	SP	TG	TF	SM
Cheapest Cost Alternative	C 1–1	SF 2–1	SP 1–1	TG 1–1	TF 1–1	SM 1–1
f_i —Primary Axis Grid [m]	12	12	12	12	12	12
N_f —Primary Axis Fields	4	4	4	4	4	4
g_j —Secondary Axis Grid [m]	6	12	6	6	6	6
N_g —Secondary Axis Fields	20	10	20	20	20	20
Net Costs [in k €]	921	784	1 056	546	516	778
O4—Retrofittability	1.00	1.00	1.00	1.00	1.00	1.00
O5—Expandability	0.14	0.14	0.14	0.14	0.14	0.14
O6—Flexibility in space	0.78	0.65	0.89	0.71	0.53	0.65
O7—Flexibility in floor plan	0.00	0.14	0.00	0.00	0.00	0.00
Flexibility Rating	0.48	0.48	0.51	0.46	0.42	0.45
<i>O4—Variant no retrofiting</i>						
$F_{RF} = 0.00 \text{ kN/m}^2$	0.00	0.00	0.00	0.00	0.00	0.00
Flexibility Rating	0.23	0.23	0.26	0.21	0.17	0.20

better than small axis grids, meet the requirements in industrial building projects. Stakeholders demand column-free halls und maximum span width. In addition, trusses must perform better than high solid wall girders, since technical services can be passed through openings of trusses, which increases flexibility.

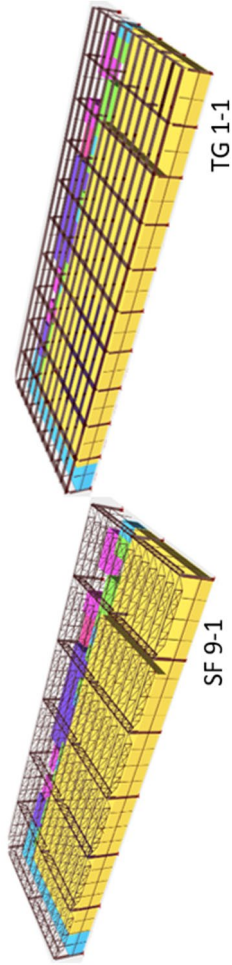


Fig. 5 Visualization of the most flexible alternative (steel framework SF-9-1) and the lowest cost alternative (timber girder TG-1-1) in Rhino3D

Concluding, the flexibility is reduced by about 10% if the column grid dimension is reduced from the highest axis grid constellation to the smallest possible variant. Furthermore, the flexibility rating is downgraded by another 25% if the structural system is not able to bear increased future loads for retrofitting.

At this point, it would be up to the decision-maker to decide whether the project should strive for more flexibility or for minimal costs. However, the test case confirms the efficiency of parametric design process for DSE and decision-support by presenting feasible design alternatives within the solution space.

6 Conclusion

Product individualization and fast changing technologies result in increased complexity and frequent reconfiguration of manufacturing systems, thus flexibility has become an increasingly important aspect in industrial building design. Industrial buildings must strive for highly flexible building structures to accommodate constantly evolving production processes and to subsequently prolong the service life and reduce life-cycle costs. To maximize the flexibility of industrial buildings, thus to increase sustainability, the focus should be on a coherent planning of building and manufacturing systems and a performance-based optimization of the load-bearing structure. However, common sustainability assessment tools do not respect flexibility metrics in the process and manufacturing and building design processes run sequentially, neglecting discipline-specific interaction, which lead to inflexible solutions. Integration is especially crucial for the early design stage of industrial buildings as decisions made on building and manufacturing flexibility are more impactful when made at conceptual stage. Integrated industrial building design (IIBD) aims to incorporate building and manufacturing disciplines and criteria simultaneously. Methods for data integration and systematic optimization and decision support in early design stage to maximize the buildings flexibility are lacking in IIBD. Performance-based parametric design tools to enable design teams receive quick feedback about how different design alternatives behave and give sufficient guidance for decision-making, but no general approach for IIBD is available yet.

This paper proposes a novel design process based on parametric modeling, performance-based structural optimization and numeric flexibility assessment for IIBD, to overcome the mentioned limitations. Four novel flexibility metrics (Retrofittability, Expandability, Flexibility in space and Flexibility in floor plan) and a computer understandable design space representation for parametric design exploration in IIBD are presented. Next to this, a parametric model framework for design space exploration (DSE) with automated structural optimization and quantitative flexibility assessment of industrial building design is developed.

Results of the test case, evaluating the parametric model framework on a representative industrial construction project, confirmed the efficiency of the parametric design process for DSE and decision-support by presenting feasible design alternatives within the solution space. Stakeholders involved in industrial building projects aim for maximum flexibility but lowest possible costs. The validation

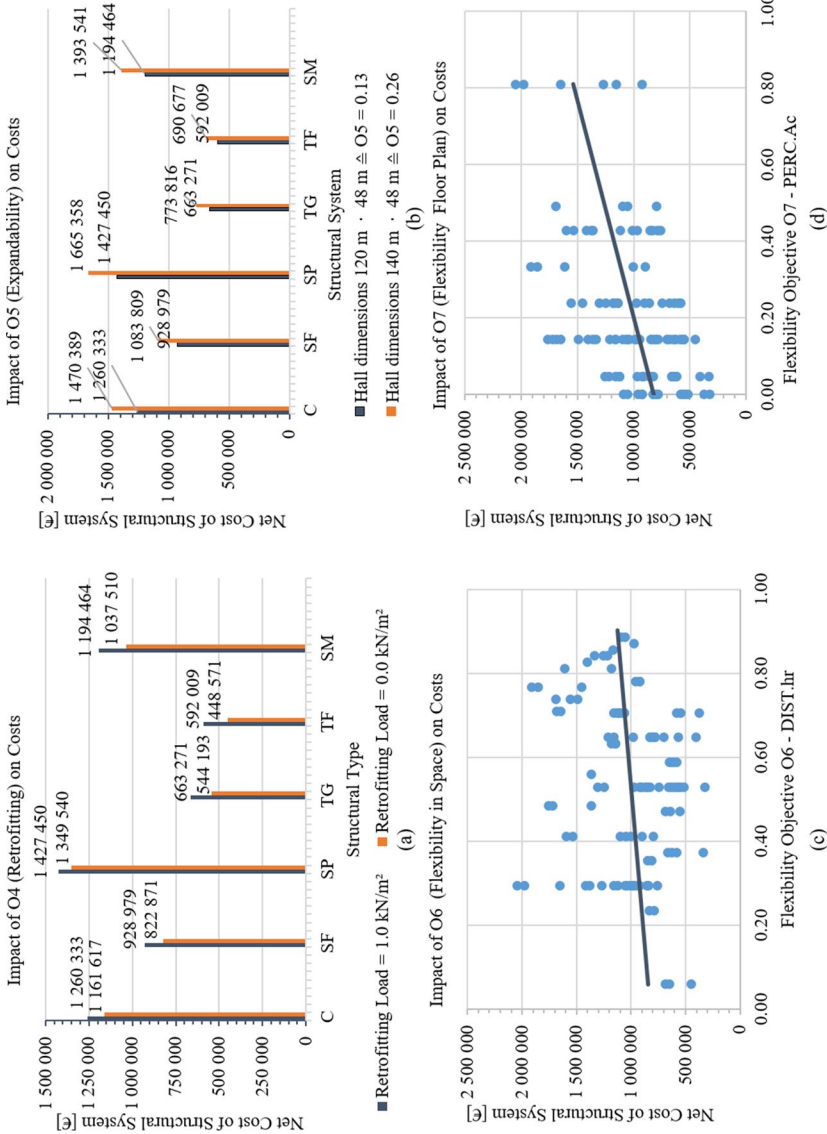


Fig. 6 Impact analysis of the flexibility objectives on the costs of the structure: **a** cost impact of O4, the retrofitting ability; **b** cost impact of O5, the expandability; **c** cost impact of O6, the flexibility in space and **d** cost impact of O7, the flexibility of the floor plan

of the defined flexibility metrics, examined in trade-off with the net cost of the structural system, revealed the accuracy of the metrics derivation and realistic results were achieved. The proposed process enables IIBD teams to quickly perform variant studies and review the impact of design decisions in order to guide the decision process towards maximum flexible, thus resource efficient designs.

However, in order to find sustainable and economic building solutions and to offer a holistic sustainability assessment approach, economic and environmental trade-offs, such as life cycle costs, life-cycle assessment and the evaluation of the recycling rate, should be considered next to the trade-off of flexibility, which will be the next step of the research. The flexibility metrics and the net costs were equally weighted in this study in order to make them valid able and comparable, but objectives in multidisciplinary design problems can be to some degree competing and principles for proper weighting are needed. The different stakeholder objective preferences in IIBD will be taken into account and are incorporated into the decision-making process in a structured, systematic and transparent way in following research steps.

The results of the presented work are important prerequisites for future research, in which an evolutionary multi-objective algorithm for efficient multidisciplinary design optimization will be implemented in the parametric design process. The proposed design space representation for IIBD aimed to reduce the number of design options in the search, thus to consider fast and feasible results during multi-objective optimization later on. Thus, the space of the designs can be more efficiently generated and explored. The developed basis of the parametric model framework offers a vast computational infrastructure, which is extendable to the scope of IIBD analysis, giving the opportunity to integrate other aspects such as energy performance or production system simulations more quickly and guide early decision making towards economic, ecological and flexible design solutions.

Acknowledgements The authors would like to acknowledge the support by the Austrian funding institution FFG (Österreichische Forschungsförderungsgesellschaft) for the research project “BIMFlexi” within the FFG BRIDGE (30th call for tenders) programme (Grant No. 877159). We would particularly like to thank Patrick Hollinsky and Maria Antonia Zahlbruckner supporting in the case study and those experts of our industry partners who agreed to be interviewed.

Funding Open access funding provided by TU Wien (TUW).

Open Access This article is licensed under a Creative Commons Attribution 4.0 International License, which permits use, sharing, adaptation, distribution and reproduction in any medium or format, as long as you give appropriate credit to the original author(s) and the source, provide a link to the Creative Commons licence, and indicate if changes were made. The images or other third party material in this article are included in the article's Creative Commons licence, unless indicated otherwise in a credit line to the material. If material is not included in the article's Creative Commons licence and your intended use is not permitted by statutory regulation or exceeds the permitted use, you will need to obtain permission directly from the copyright holder. To view a copy of this licence, visit <http://creativecommons.org/licenses/by/4.0/>.

References

- Baril C, Yacout S, Clément B (2012) An interactive multi-objective algorithm for decentralized decision making in product design. *J Optim Eng* 13:121–150. <https://doi.org/10.1007/s11081-011-9148-0>
- Beach R, Muhlemann AP, Price DHR, Paterson A, Sharp JA (2000) A review of manufacturing flexibility. *Eur J Op Res* 122:41–57. [https://doi.org/10.1016/S0377-2217\(99\)00062-4](https://doi.org/10.1016/S0377-2217(99)00062-4)
- Bejjani C, Utsch J, Thiele T, Meisen T, Jeschke S, Burggräf P (2018) Flow chart based information modeling for factory planning. *J Proc CIRP* 72:410–415. <https://doi.org/10.1016/j.procir.2018.03.259>
- Bleicher F, Duer F, Leobner I, Kovacic I, Heinzl B, Kastner W (2014) Co-simulation environment for optimizing energy efficiency in production systems. *J CIRP Ann* 63:441–444. <https://doi.org/10.1016/j.cirp.2014.03.122>
- Brown NC, Jusiega V, Mueller CT (2020) Implementing data-driven parametric building design with a flexible toolbox. *J Autom Constr* 118:103252. <https://doi.org/10.1016/j.autcon.2020.103252>
- Brown NC, Mueller CT (2016) Design for structural and energy performance of long span buildings using geometric multi-objective optimization. *J Energy Build* 127:748–761. <https://doi.org/10.1016/j.enbuild.2016.05.090>
- Browne J, Dubois D, Rathmill K, Sethi S, Stecke K (1984) Classification of Flexible Manufacturing Systems. *The FMS Mag* 2:115–117
- Büscher C, Meisen T, Schilberg D, Jeschke S (2016) VPI-FP: an integrative information system for factory planning. *Int J Prod Res* 54:2215–2226. <https://doi.org/10.1080/00207543.2015.1057298>
- Büscher C et al (2014) Improving factory planning by analyzing process dependencies. *J Proc CIRP* 17:38–43. <https://doi.org/10.1016/j.procir.2014.01.142>
- Cavalliere C, Dell’Osso GR, Favia F, Lovicario M (2019) BIM-based assessment metrics for the functional flexibility of building designs. *J Autom Constr* 107:102925. <https://doi.org/10.1016/j.autcon.2019.102925>
- Cellucci C, Sivo M (2015) The flexible housing: criteria and strategies for implementation of the flexibility. *J Civil Eng Arch* 9:845–852. <https://doi.org/10.17265/1934-7359/2015.07.011>
- Chen D, Heyer S, Seliger G, Kjellberg T (2012) Integrating sustainability within the factory planning process. *J CIRP Ann Manuf Technol* 61:463–466. <https://doi.org/10.1016/j.cirp.2012.03.067>
- Chinese D, Nardin G, Saro O (2011) Multi-criteria analysis for the selection of space heating systems in an industrial building. *J Energy* 36:556–565. <https://doi.org/10.1016/j.energy.2010.10.005>
- Cousens A, Szwajczewski M, Sweeney M (2009) A process for managing manufacturing flexibility. *Int J Oper Prod Manage* 29:357–385. <https://doi.org/10.1108/01443570910945828>
- Cuadrado J, Zubizarreta M, Roji E, García H, Larrauri M (2015) Sustainability-related decision making in industrial buildings: An AHP analysis. *J Math Prob Eng* 2015:1–13. <https://doi.org/10.1155/2015/157129>
- De Paris SR, Lopes CNL (2018) Housing flexibility problem: review of recent limitations and solutions. *Front Arch Res* 7:80–91. <https://doi.org/10.1016/j.foar.2017.11.004>
- Deif AM (2011) A system model for green manufacturing. *J of Clean Prod* 19:1553–1559. <https://doi.org/10.1016/j.jclepro.2011.05.022>
- Ebade Esfahani M, Burggräf P, Dannapfel M, Schneidermann D, Schwamborn N (2019) Integrated factory modelling: Using BIM to disrupt the interface between manufacturing and construction in factory planning. *J WIT Trans Built Environ* 192:143–155. <https://doi.org/10.2495/BIM190131>
- Eisenhardt K (1989) Building theories from case study research. *Acad Manag Rev* 14:532–550. <https://doi.org/10.2307/258557>
- Eisenhardt KM, Graebner ME (2007) Theory building from cases: opportunities and challenges. *Acad Manag J* 50:25–32. <https://doi.org/10.5465/amj.2007.24160888>
- ElMaraghy H, Wiendahl H-P (2014) Changeable manufacturing. In: Laperrière L, Reinhart G (eds) *CIRP encyclopedia of production engineering*. Springer, Heidelberg
- Emmerich MTM, Deutz AH (2018) A tutorial on multiobjective optimization: fundamentals and evolutionary methods. *J Nat Comput* 17:585–609. <https://doi.org/10.1007/s11047-018-9685-y>
- Evins R (2013) A review of computational optimisation methods applied to sustainable building design. *Renew Sustain Energy Rev* 22:230–245. <https://doi.org/10.1016/j.rser.2013.02.004>
- Finnveden G, Moberg Å (2005) Environmental systems analysis tools – an overview. *J of Clean Prod* 13:1165–1173. <https://doi.org/10.1016/j.jclepro.2004.06.004>

- Francalanza E, Borg J, Constantinescu C (2017) Development and evaluation of a knowledge-based decision-making approach for designing changeable manufacturing systems. *CIRP J Manuf Sci Technol* 16:81–101. <https://doi.org/10.1016/j.cirpj.2016.06.001>
- Garwood TL, Hughes BR, Oates MR, O'Connor D, Hughes R (2018) A review of energy simulation tools for the manufacturing sector. *Renew Sustain Energy Rev* 81:895–911. <https://doi.org/10.1016/j.rser.2017.08.063>
- Geraedts R (2016) FLEX 4.0, A practical instrument to assess the adaptive capacity of buildings. *J Energy Procedia* 96:568–579. <https://doi.org/10.1016/j.egypro.2016.09.102>
- Glumac B, Islam N (2020) Housing preferences for adaptive re-use of office and industrial buildings: demand side. *J Sustain Cities Soc* 62:102379. <https://doi.org/10.1016/j.scs.2020.102379>
- Gosling J, Naim M, Sassi P, Iosif L, Lark R (2009) Flexible buildings for an adaptable and sustainable future. In: Dainty AEPTAAC (Ed) Association of Researchers in Construction Management, Cardiff, UK, 1–3 September 2008. pp 115–124
- Gourlis G, Kovacic I (2016) A study on building performance analysis for energy retrofit of existing industrial facilities. *J Appl Energy* 184:1389–1399. <https://doi.org/10.1016/j.apenergy.2016.03.104>
- Graefenstein J, Winkels J, Lenz L, Weist KC, Krebil K, Gralla M (2020) A hybrid approach of modular planning—synchronizing factory and building planning by using component based synthesis. In: Proceedings of 53rd Hawaii international conference on system sciences, pp 6580–6588. <https://doi.org/10.24251/HICSS.2020.806>
- Hawer S, Sager B, Braun H, Reinhart G (2017) An adaptable model for the factory planning process: analyzing data based interdependencies. *J Proc CIRP* 62:117–122. <https://doi.org/10.1016/j.procir.2016.06.003>
- Haymaker J et al (2018) Design space construction: a framework to support collaborative, parametric decision making. *J Inf Technol Const (ITcon)* 23:157–178
- Heravi G, Fathi M, Faeghi S (2015) Evaluation of sustainability indicators of industrial buildings focused on petrochemical projects. *J Clean Prod* 109:92–107. <https://doi.org/10.1016/j.jclepro.2015.06.133>
- Heravi G, Fathi M, Faeghi S (2017) Multi-criteria group decision-making method for optimal selection of sustainable industrial building options focused on petrochemical projects. *J Clean Prod* 142:2999–3013. <https://doi.org/10.1016/j.jclepro.2016.10.168>
- Honic M, Kovacic I, Rechberger H (2019) Improving the recycling potential of buildings through Material Passports (MP): an Austrian case study. *J Clean Prod* 217:787–797. <https://doi.org/10.1016/j.jclepro.2019.01.212>
- Huettemann G, Gaffry C, Schmitt RH (2016) Adaptation of reconfigurable manufacturing systems for industrial assembly – review of flexibility paradigms, concepts, and outlook. *J Proc CIRP* 52:112–117. <https://doi.org/10.1016/j.procir.2016.07.021>
- Israelsson N (2009) Factors influencing flexibility in buildings. *J Struct Surv* 27:138–147. <https://doi.org/10.1108/02630800910956461>
- Kampker A, Meckelnborg A, Burggräf P, Netz T Factory planning scrum : integrative factory planning with agile project management. In: Manufacturing PICoC (ed) COMA´ 13, Stellenbosch, South Africa, 30 January - 1 February 2013 2013. pp 345–350
- Kang E, Jackson E, Schulte W (2010) An approach for effective design space exploration. In: Paper presented at Monterey Workshop foundations of computer software. Modeling, development, and verification of adaptive systems. Springer, Berlin, Heidelberg pp 33–54
- Kara S, Kayis B (2004) Manufacturing flexibility and variability: an overview. *J Manuf Technol Manag* 15:466–478. <https://doi.org/10.1108/17410380410547870>
- Kluczek A (2017) An overall multi-criteria approach to sustainability assessment of manufacturing processes. *J Proc Manuf* 8:136–143. <https://doi.org/10.1016/j.promfg.2017.02.016>
- Kontogiannis SG, Savill MA (2020) A generalized methodology for multidisciplinary design optimization using surrogate modelling and multifidelity analysis. *J Optim Eng* 21:723–759. <https://doi.org/10.1007/s11081-020-09504-z>
- Kovacic I, Waltenberger L, Gourlis G (2016) Tool for life cycle analysis of facade-systems for industrial buildings. *J Clean Prod* 130:260–272. <https://doi.org/10.1016/j.jclepro.2015.10.063>
- Lee B, Pourmousavian N, Hensen JLM (2016) Full-factorial design space exploration approach for multi-criteria decision making of the design of industrial halls. *J Energy Build* 117:352–361. <https://doi.org/10.1016/j.enbuild.2015.09.028>
- Lee JH, Ostwald MJ (2020) Creative decision-making processes in parametric design. *J Build* 10:242. <https://doi.org/10.3390/buildings10120242>

- Lenz LT, Gralla M, Höpfner M, Spyridis P, Weist KC (2019) BIM approach for decision support: case study fastening systems in factory adaptation planning. In: Proceedings of the 2019 European conference on computing in construction EC3, Greece, Crete. pp 2–8. doi:<https://doi.org/10.35490/EC3.2019.136>
- Löffler C, Westkämper E, Unger K (2012) Changeability in structure planning of automotive manufacturing. *J Proc CIRP* 3:167–172. <https://doi.org/10.1016/j.procir.2012.07.030>
- Machairas V, Tsangrassoulis A, Axarli K (2014) Algorithms for optimization of building design: a review. *J Renew Sustain Energy Rev* 31:101–112. <https://doi.org/10.1016/j.rser.2013.11.036>
- Makris M, Gerber D, Carlson A, Noble D (2013) Informing design through parametric integrated structural simulation: iterative structural feedback for design decision support of complex trusses. In: eCAADe Computation and Performance Delft, NL, 18–20 September 2013, pp 69–77
- Marjaba G, Chidiac SE (2016) Sustainability and resiliency metrics for buildings – Critical review. *J Build Environ* 101:116–125. <https://doi.org/10.1016/j.buildenv.2016.03.002>
- Méndez Echenagucia T, Capozzoli A, Cascone Y, Sassone M (2015) The early design stage of a building envelope: Multi-objective search through heating, cooling and lighting energy performance analysis. *J Appl Energy* 154:577–591. <https://doi.org/10.1016/j.apenergy.2015.04.090>
- Montellano A (2015) Housing flexibility by spatial indeterminacy: the case of the casa de las Flores in Madrid. *Archnet-IJAR* 9:4–19. <https://doi.org/10.26687/archnet-ijar.v9i2.661>
- Motta E (1998) Reusable components for knowledge modelling. Dissertation, The Open University:346. doi:<https://doi.org/https://doi.org/10.21954/ou.ro.0000e217>
- Mousavi S, Thiede S, Li W, Kara S, Herrmann C (2016) An integrated approach for improving energy efficiency of manufacturing process chains. *Int J Sustain Eng* 9:11–24. <https://doi.org/10.1080/19397038.2014.1001470>
- Mueller CT (2014) Computational exploration of the structural design space. Dissertation, Massachusetts Institute of Technology
- Mueller CT, Ochsendorf JA (2015) Combining structural performance and designer preferences in evolutionary design space exploration. *J Autom Constr* 52:70–82. <https://doi.org/10.1016/j.autcon.2015.02.011>
- Nyhuis P, Heinen T, Brieke M (2007) Adequate and economic factory transformability and the effects on logistical performance. *Int J Flex Manuf Syst* 19:286–307. <https://doi.org/10.1007/s10696-007-9027-3>
- Pan W, Sun Y, Turrin M, Louter C, Sariyildiz S (2020) Design exploration of quantitative performance and geometry typology for indoor arena based on self-organizing map and multi-layered perceptron neural network. *J Autom Constr* 114:103163. <https://doi.org/10.1016/j.autcon.2020.103163>
- Preisinger C, Heimrath M (2014) Karamba—A toolkit for parametric structural design. *J Struct Eng Int* 24:217–221. <https://doi.org/10.2749/101686614X13830790993483>
- Röck M, Hollberg A, Habert G, Passer A (2018) LCA and BIM: Visualization of environmental potentials in building construction at early design stages. *J Build Environ* 140:153–161. <https://doi.org/10.1016/j.buildenv.2018.05.006>
- Rodrigues V, Martins AA, Nunes MI, Quintas A, Mata TM, Caetano NS (2018) LCA of constructing an industrial building: focus on embodied carbon and energy. *J Energy Proc* 153:420–425. <https://doi.org/10.1016/j.egypro.2018.10.018>
- Sadafi N, Zain MFM, Jamil M (2014) Design criteria for increasing building flexibility: dynamics and prospects. *Environ Eng Manag J* 13:407–417. <https://doi.org/10.30638/eemj.2014.045>
- San-José Lombera J-T, Garrucho Aprea I (2010) A system approach to the environmental analysis of industrial buildings. *J Build Environ* 45:673–683. <https://doi.org/10.1016/j.buildenv.2009.08.012>
- Schuh G, Kampker A, Wesch-Potente C (2011) Condition based factory planning. *J Prod Eng* 5:89–94. <https://doi.org/10.1007/s11740-010-0281-y>
- Sethi AK, Sethi SP (1990) Flexibility in manufacturing: a survey. *Int J Flex Manuf Syst* 2:289–328. <https://doi.org/10.1007/BF00186471>
- Shan M, Hwang B-g (2018) Green building rating systems: global reviews of practices and research efforts. *J Sustain Cities Soc* 39:172–180. <https://doi.org/10.1016/j.scs.2018.02.034>
- Shewchuk JP, Moodie CL (1998) Definition and classification of manufacturing flexibility types and measures. *Int J Flex Manuf Syst* 10:325–349. <https://doi.org/10.1023/A:1008062220281>
- Slaughter ES (2001) Design strategies to increase building flexibility. *J Build Res Inf* 29:208–217. <https://doi.org/10.1080/09613210010027693>
- Sóbestera A, Powell S (2013) Design space dimensionality reduction through physics-based geometry reparameterization. *J Optim Eng* 14:37–59. <https://doi.org/10.1007/s11081-012-9189-z>

- Till J, Schneider T (2006) Flexible housing: the means to the end. *J Arch Res Q* 9:287–296. <https://doi.org/10.1017/S1359135505000345>
- Tulevech SM, Hage DJ, Jorgensen SK, Guensler CL, Himmler R, Gheewala SH (2018) Life cycle assessment: a multi-scenario case study of a low-energy industrial building in Thailand. *J Energy Build* 168:191–200. <https://doi.org/10.1016/j.enbuild.2018.03.011>
- Turrin M, Von Buelow P, Stouffs R (2011) Design explorations of performance driven geometry in architectural design using parametric modeling and genetic algorithms. *J Adv Eng Inf* 25:675. <https://doi.org/10.1016/j.aei.2011.07.009>
- Vardopoulos I (2019) Critical sustainable development factors in the adaptive reuse of urban industrial buildings. A fuzzy DEMATEL approach. *J Sustain Cities Soc* 50:101684. <https://doi.org/10.1016/j.scs.2019.101684>
- Wiendahl HP, ElMaraghy HA, Nyhuis P, Zäh MF, Wiendahl HH, Duffie N, Briekle M (2007) Changeable manufacturing - classification, design and operation. *J CIRP Annals* 56:783–809. <https://doi.org/10.1016/j.cirp.2007.10.003>
- Yin RK (2009) *Case study research: design and methods*. Sage Publ, Los Angeles
- Živković M, Jovanović G (2012) A method for evaluating the degree of housing unit flexibility in multi-family housing. *J Arch Civil Eng* 10:17–32. <https://doi.org/10.2298/FUACE1201017Z>

Publisher's Note Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.