Doctoral Thesis

Parametric optimization and decision support framework for the realization of flexible and sustainable industrial buildings incorporating production planning at early design stage

submitted in satisfaction of the requirements for the degree of
Doctor of Science in Civil Engineering
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Dissertation

Framework zur parametrischen Optimierung- und Entscheidungsunterstützung für die Realisierung von flexiblen und nachhaltigen Industriebauten unter Einbeziehung der Produktionsplanung in der frühen Entwurfsphase

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Abstract

Industrial buildings play a critical role in sustainable development, producing and consuming a significant amount of costs, resources, energy and waste. Emerging technologies in Industry 4.0 digitize and automate manufacturing and aim to realize batch size 1 production and product individualization on demand. These rapid technological advances require frequent reconfiguration and expansion of production systems. It is the load-bearing structure of industrial buildings that is most rigid and durable, limiting the buildings ability to adapt to changing production processes, forcing early rescheduling or demolition, thus severely limiting the service life. A consideration of manufacturing reconfiguration scenarios during early structural design could facilitate flexible industrial buildings which can be adapted without requiring rescheduling or demolition, improving sustainability and resource efficiency. Yet, current production layout planning and structural design processes run sequential, data and digital models lack interoperability, and common performance assessment methods do not evaluate the flexibility of industrial buildings.

The two main research questions of this cumulative doctoral thesis are: How to integrate structural design and production layout planning at early design stage? How can a framework for a structural optimization and decision support method measure the flexibility of industrial building designs with respect to changing production scenarios and assess the structure-related economic and environmental impacts?

The result of this dissertation is the parametric optimization and decision support (POD) framework for early stage industrial building design. The POD framework enables automated structural analysis with simultaneous performance assessment of life cycle cost (LCC), life cycle assessment (LCA), recycling potential, and flexibility, integrating a dynamic parametric production planning method. Using the proposed framework, the designers can assess the impact of changing production processes on the economic and environmental footprint of industrial buildings, and can optimize the resource efficiency and durability through advanced performance feedback and decision support.

This dissertation closes the research gap of an integrated design process for joint production layout and structural design in early design stages and provides a method for incorporating flexibility metrics besides traditional economic and ecologic performance assessment of building structures. The novel contribution is the offering of a new method to integrate, predict, and jointly optimize industrial building structures and layouts towards maximum flexibility, providing an early stage optimization and decision support method for coherent performance improvement.

The following research steps and developments were created to ultimately form the overall POD framework. First, based on a literature review and an exploratory multiple-case study, a systematic design guideline for flexible design of industrial buildings incorporating production parameters was developed. From these findings, an integrated parametric design space and four flexibility metrics could be defined. The design space representation and flexibility metrics were translated into a parametric optimization and decision support model (POD model) for automated generation, analysis and dimensioning of industrial load-bearing structures, integrating a method for automated flexibility assessment. Based on a novel defined integrated production cubes concept, a method for parametric automated generation and optimization of production layouts (PLGO model) was developed, enabling to integrate generated layout scenarios with associated relevant building information directly into the POD model. Finally, the POD model and PLGO model were combined to form the POD framework, and a method for simultaneous assessment of LCC, LCA, recycling potential, and flexibility performance of building structures and enclosure systems was integrated into the parametric design process. The proposed integrated parametric design process is tested by means of a variant study on a pilot project from the food and hygiene production sector. The results demonstrate the effectiveness of the framework to identify potential economic and environmental savings, specify alternative building materials, and find environmentally friendly and flexible industrial building structures at early design stage, while considering different production layouts. Significant differences in costs, CO_2 emissions, and flexibility of the examined structural variants could be identified, highlighting the importance that early variant studies with integrated computational design approaches contribute to resource efficiency and sustainable development of the built environment.

In future research, an evolutionary multi-objective optimization algorithm will be implemented into the POD model to fully automate the design search and to provide a wider spectrum of possible building solutions within a reduced amount of time. Moreover, the framework will be coupled to a multi-user Virtual Reality platform to improve the visualization, interaction and decision making process for interdisciplinary teams.

This dissertation was conducted within the research project BIMFlexi (grant No. 877159), which was funded by the Austrian Ministry for Transport, Innovation and Technology (BMVIT) through the Austrian Research Promotion Agency (FFG).

Zusammenfassung

Industriegebäude spielen eine entscheidende Rolle bei der nachhaltigen Entwicklung, da sie einen erheblichen Anteil an Kosten, Ressourcen, Energie und Abfall produzieren und verbrauchen. Die aufkommenden Technologien der Industrie 4.0 digitalisieren und automatisieren die Fertigung und zielen darauf ab, die Losgröße-1-Produktion und Produktindividualisierung nach Bedarf zu realisieren. Schnelle technologische Fortschritte erfordern häufig Neukonfigurationen und Erweiterungen der Produktionssysteme. Die tragende, starre Struktur von Industriegebäuden ist am langlebigsten, und schränkt die Anpassungsfähigkeit des Gebäudes an sich ändernde Produktionsprozesse ein, was zu frühzeitigem Umbau oder Abriss führt. Die Berücksichtigung von wechselnden Produktionsprozessen während der frühen Tragwerksplanung könnte flexiblere Industriegebäude ermöglichen, die ohne Umplanung oder Abriss angepasst werden können, was die Nachhaltigkeit und Ressourceneffizienz verbessern würde. Die derzeitige Planung von Produktion- und Tragwerksplanung läuft jedoch sequentiell ab, Daten und Modelle sind nicht interoperabel, und gängige Methoden zur Nachhaltigkeitsbewertung inkludieren nicht die Flexibilität.

Die zwei Hauptforschungsfragen dieser kumulativen Dissertation lauten: Wie können Tragwerksplanung und Produktionslayoutplanung integriert werden? Wie sieht ein Framework zur Tragwerksoptimierung und Entscheidungsunterstützung aus, welcher die Flexibilität von Industriebauentwürfen im Hinblick auf sich ändernde Produktionsszenarien messen und die tragwerksbezogenen wirtschaftlichen und ökologischen Auswirkungen bewerten kann? Das Ergebnis dieser Dissertation ist ein Framework zur parametrischen Optimierung- und Entscheidungsunterstützung (POD) in frühen Planungsphasen von Industriegebäuden. Der POD-Framework ermöglicht die automatisierte Tragwerksanalyse mit gleichzeitiger Bewertung der Lebenszykluskosten (LCC), der Ökobilanz (LCA), des Recyclingpotenzials und der Flexibilität und integriert eine dynamische parametrische Produktionsplanungsmethode. Der integrale parametrische Planungsprozess ermöglicht es, die Auswirkungen verändernder Produktionsprozesse auf den ökonomischen und ökologischen Fußabdruck von Industriebauten zu berücksichtigen und verbessert dadurch die Ressourceneffizienz und Langlebigkeit der Gebäude.

Diese Dissertation schließt die Forschungslücke eines integralen Entwurfsprozesses für die gemeinsame Planung von Produktionslayout und Tragwerken in frühen Phasen und bietet eine Methode zur Einbeziehung von Flexibilitätsbewertungen neben traditionellen wirtschaftlichen und ökologischen Leistungsbewertungen. Der neuartige Beitrag besteht darin, dass eine neue Methode zur Integration, Vorhersage und gemeinsamen Optimierung von industriellen Gebäudestrukturen und -layouts im Hinblick auf maximale

Flexibilität angeboten wird, welche eine frühe Optimierung- und Entscheidungshilfe für eine kohärente Leistungsverbesserung bietet.

Die folgenden Forschungsschritte und Entwicklungen wurden durchgeführt, um den finalen POD-Framework zu bilden. Zunächst wurde auf Grundlage einer Literaturrecherche und einer explorativen Fallstudie ein systematischer Leitfaden für die flexible Gestaltung von Industriegebäuden unter Integration von Produktionsparametern entwickelt. Aus diesen Erkenntnissen konnten ein integraler parametrischer Entwurfsraum und vier Flexibilitätsmetriken definiert werden. Die Entwurfsraumdarstellung und die Flexibilitätskriterien wurden in ein parametrisches Optimierungs- und Entscheidungsunterstützungsmodell (POD-Modell) zur automatisierten Generierung, Analyse und Dimensionierung von industriellen Tragwerken übersetzt, das eine Methode zur automatisierten Flexibilitätsbewertung integriert. Basierend auf einem neu definierten „Integrated Production Cubes Concept" wurde eine Methode zur parametrischen automatisierten Generierung und Optimierung von Produktionslayouts (PLGO-Modell) entwickelt, die es ermöglicht, generierte Layout Szenarien mit zugehörigen relevanten Gebäudeinformationen direkt in das POD-Modell zu integrieren. Schließlich wurden das POD-Modell und das PLGO-Modell zum POD-Rahmenwerk kombiniert und eine Methode zur gleichzeitigen Bewertung von LCC, LCA, Recyclingpotenzial und Flexibilität von Gebäudestrukturen und -hüllen integriert. Das entwickelte parametrische Rahmenwerk wurden anhand einer Variantenstudie an einem Pilotprojekt aus dem Bereich der Lebensmittel- und Hygieneproduktion getestet. Die Ergebnisse zeigen die Effektivität des POD-Modellrahmens zur Identifikation potenzieller wirtschaftlicher und ökologischer Einsparungen, zur Spezifizierung alternativer Baumaterialien und zur Suche nach umweltfreundlichen und flexiblen Gebäudestrukturen in frühen Planungsphasen. Es konnten signifikante Unterschiede bei den Kosten, den CO_2-Emissionen und der Flexibilität der untersuchten Gebäudevarianten identifiziert werden, was die Bedeutung früher Variantenstudien mit integralen computergestützten Entwurfsansätzen hervorhebt, um einen Beitrag zur Ressourceneffizienz und zur nachhaltigen Entwicklung der gebauten Umwelt zu leisten. In zukünftigen Forschungsarbeiten wird ein evolutionärer Optimierungsalgorithmus in das POD-Modell implementiert, um die Entwurfssuche zu automatisieren. Der Framework wird mit einer Multi-User-Virtual-Reality-Plattform gekoppelt, um die Visualisierung und den Entscheidungsfindungsprozess zu verbessern.

Diese Dissertation wurde im Rahmen des Forschungsprojekts BIMFlexi (Nr. 877159) durchgeführt, das vom österreichischen Bundesministerium für Verkehr, Innovation und Technologie (BMVIT) über die Österreichische Forschungsförderungsgesellschaft (FFG) gefördert wurde.

List of Publications

J. Reisinger, P. Hollinsky, I. Kovacic: "*Design Space Representation for Multi-Criteria Decision Making in Energy- and Resource Efficient Industrial Building Design*"; in: "*15th Conference on Sustainable Development of Energy, Water and Environment Systems - Book of Abstracts*", (2020), ISSN: 2706-3690; 313.

J. Reisinger, I. Kovacic, H. Kaufmann, P. Kán, I. Podkosova: "*Framework proposal for a BIM-based digital platform for flexible design and optimization of industrial buildings for industry 4.0*"; in: "*Proceedings of the 37th International CIB W78 Conference 2020*", online, 37, São Paulo, Brazil (online); 08-18-2020 - 08-20-2020 (2020), ISSN: 2706-6568; 401 - 415. Doi: 10.46421/2706-6568.37.2020.paper029

J. Reisinger, M. Knoll, I. Kovacic: "*Parametric Structural Design for automated Multi-Objective Optimization of Flexible Industrial Buildings*"; in: "*2020 Proceedings of the 37th ISARC, Kitakyushu, Japan*", International Association for Automation and Robotics in Construction (IAARC), Japan (online);10-27-2020 - 10-28-2020, ISBN: 978-952-94-3634-7; 185 – 192. Doi: 10.22260/ISARC2020/0028

J. Reisinger, M. Knoll, I. Kovacic: "*Design space exploration for flexibility assessment and decision making support in integrated industrial building design*"; Optimization and Engineering (invited), 22 (2021), 1693–1725, 33 pages. Doi:10.1007/s11081-021-09614-2

J. Reisinger, M. Zahlbruckner, I. Kovacic, P. Kán, X. Wang-Sukalia: "*Framework proposal for automated generation of production layout scenarios: A parametric design technique to connect production planning and structural industrial building design*"; in: "*EG-ICE 2021 Workshop on Intelligent Computing in Engineering*", Berlin, Deutschland; 06-30-2021 - 07-02-2021; Universitätsverlag der TU Berlin, 28 (2021), ISBN: 978-3-7983-3212-6; 22 - 33.

J. Reisinger, I. Kovacic: "*Parametric structural optimisation tool for flexible industrial buildings: evaluation through experimental study*"; EC3 2021 European Conference on Computing in Construction, Rhodos, Greece; 07-26-2021 - 07-28-2021; in: "*2021 European Conference on Computing in Construction*", (2021). Doi: 10.35490/EC3.2021.149

J. Reisinger, P. Hollinsky, I. Kovacic: "*Design Guideline for Flexible Industrial Buildings Integrating Industry 4.0 Parameters*"; Sustainability (invited), 13 (2021), 19; 10627. Doi:10.3390/su131910627

J. Reisinger, S. Kugler, M. Knoll, I. Kovacic: "*Integration of Environmental Impact Assessment into Parametric Performance-Based Structural Design for Flexible Industrial Buildings*"; in: "16th Conference on Sustainable Development of Energy, Water and Environment Systems", Dubrovnik (invited); 10-10-2021 - 10-15-2021, ISSN: 1847-7178; 377.

J. Reisinger, M. Zahlbruckner, I. Kovacic, P. Kán, X. Wang-Sukalia, H. Kaufmann: "*Integrated multi-objective evolutionary optimization of production layout scenarios for parametric structural design of flexible industrial buildings*"; Journal of Building Engineering, 46 (2022). Doi: 10.1016/j.jobe.2021.103766

J. Reisinger, S. Kugler, I. Kovacic and M. Knoll: "*Integrated parametric optimization and decision support model to conduct life cycle cost analysis and life cycle assessment of flexible industrial buildings.*" Buildings, 12 (2022), Doi:10.3390/buildings12020162

I. Podkosova, J. Reisinger, H. Kaufmann, I. Kovacic: „*BIMFlexi-VR: A Virtual Reality Framework for Early-Stage Collaboration in Flexible Industrial Building Design.*" Frontiers in Virtual Reality, 3 (2022). Doi: 10.3389/frvir.2022.782169

List of abbreviations

AP	Acidification Potential
BIM	Building Information Modelling
CO_2	Carbon dioxide
EE	Embodied energy
GFA	Gross Floor Area
GWP	Global Warming Potential
LCA	Life Cycle Assessment
LCC	Life Cycle Cost
MJ	Mega Joule
PEI	Primary Energy Intensity
PEIn	Primary Energy Intensity Non-Renewable
PLGO	Production Layout Generation and Optimization
POD	Parametric Optimization and Decision-Support
SO_2	Sulfur dioxide

Structure of the work

- **Section I** – **Synthesis** – summarizes the research objectives, methodology and results of this cumulative doctoral thesis. It presents the state of the art review of the main topics of flexibility assessment, life cycle assessment, recycling potential assessment and life cycle cost analysis, as well as emerging parametric performance based design and integrated industrial building design methods. Subsequently, the objectives of the thesis are outlined, followed by the presentation of the used methodology. Finally, the research papers are summarized and a conclusion and future outlook is given.
- **Section II – Research papers** – presents the four scientific peer-reviewed research papers.

Section I

Synthesis

1 Introduction

1.1 Problem Statement

Climate change, resource scarcity, and economic bottlenecks make the built environment a critical consumer of economic and environmental resources. A significant amount of energy, materials, and waste are produced and used for construction of industrial buildings, requiring a large amount of materials for foundations, load-bearing structures, roofs, walls, and cladding [1, 2]. The aim of Industry 4.0 is to emphasize highly networked, automated and individualized production [3], which shortens production cycles and entails regular reconfiguration and expansion of production systems. Considering that load-bearing structures are very rigid and have the longest service life in a building [4], flexible and expandable production layouts pose high challenges to the structural design. The rapid changes in production processes result in a relatively short service life of industrial buildings compared to traditional building types. To avoid premature rescheduling and demolition, the load-bearing structure must be analyzed and optimized with respect to flexibility, while incorporating the synergy effects of production systems already at early design stage [5]. Due to upcoming sustainability requirements, a more integrated practice at early design stage is needed. Digital structural design methods that integrate production layout planning and provide decision support could support the design of flexible industrial buildings and improve the economic and environmental sustainability of industrial building projects. However, three major obstacles can be identified:

1.) Although flexibility considerations have the potential to improve the sustainability of production processes [6] and building designs [7], flexibility is rarely considered in the architectural and engineering design of manufacturing facilities [8]. There is a lack of common formulation of flexibility metrics and digital methods to assess the flexibility of industrial buildings.

2.) Digital design models do not properly address the interaction between production and building disciplines. Typical manufacturing and building design methods are configured in a domain-specific manner and lack heterogeneous data integration and interoperability. A sequential planning process and discipline-specific silo-working culture make it difficult to provide interactive, interdisciplinary decision support at early design stage [9-11]. Most integrated factory models focus on Building Information Modelling (BIM) methods, however, BIM is not appropriate for early structural simulations and variant studies.

3.) Structural design considerations usually enter the design process at later stages and are subordinate to decisions on architectural design [12] and production layout planning [10]. The majority of structural analysis methodologies just provide feedback to the structural engineer and do not support an integrated performance improvement strategy [13]. Parametric design methods have the potential to shift structural design to early stages, support collaboration, interdisciplinary simulation, and real-time performance evaluation [14, 15]. However, these methods solely dimension the structure according to structural performance and do not integrate environmental, economic and flexibility assessment methods for holistic performance optimization.

Prior research examined holistic factory planning approaches based on BIM [9, 16, 17] or from production process view [18]. Various studies conduct life cycle cost analysis (LCC) [19, 20] or life cycle assessment (LCA) [21, 22] of pre-designed or already built industrial buildings. Other researcher assess the flexibility of residential buildings [7, 23] or manufacturing systems [24, 25] or provide design strategies to realize flexible production facilities [8]. Yet, a research gap remains on how to balance economic and environmental sustainability, including flexibility of industrial buildings, and how to integrate production layout planning and structural design processes at early design stage for interdisciplinary decision support.

This doctoral thesis addresses the lack of a structural design methodology for early stage decision support that incorporates production layout planning and gives real-time feedback to economic, environmental and flexibility performance. The objective of this dissertation is to provide a digital parametric optimization and decision support (POD) framework that integrates building and production processes, evaluates the flexibility of building and production systems, and implements economic and environmental performance assessment into the early structural design process. The overall goal is improve the resource efficiency, durability and life cycle performance of industrial buildings in long term.

1.2 Research question

The focus of this dissertation is the framework development for a parametric design, optimization and decision support (POD) model for flexible industrial building structures, integrating production planning. The main research questions of this thesis are:

RQ1: How to integrate structural design and production layout planning at early design stage?

RQ2: How can a framework for a structural optimization and decision support method measure the flexibility of industrial building designs with respect to changing production scenarios and assess the structure-related economic and environmental impacts?

The following sub-questions will be investigated in order to answer the main research question, as shown in Fig. 1:

- What kind of input data is needed for the POD framework?
- How can flexibility in building and production planning be measured and integrated?
- How should the parametric modelling and design space exploration be conducted?
- How can production planning and structural design processes and tools be coupled?
- What workflow, rules and criteria is needed to automate manual processes?
- What should be the content of the POD framework to achieve adequate performance assessment results for decision making towards increased sustainability?

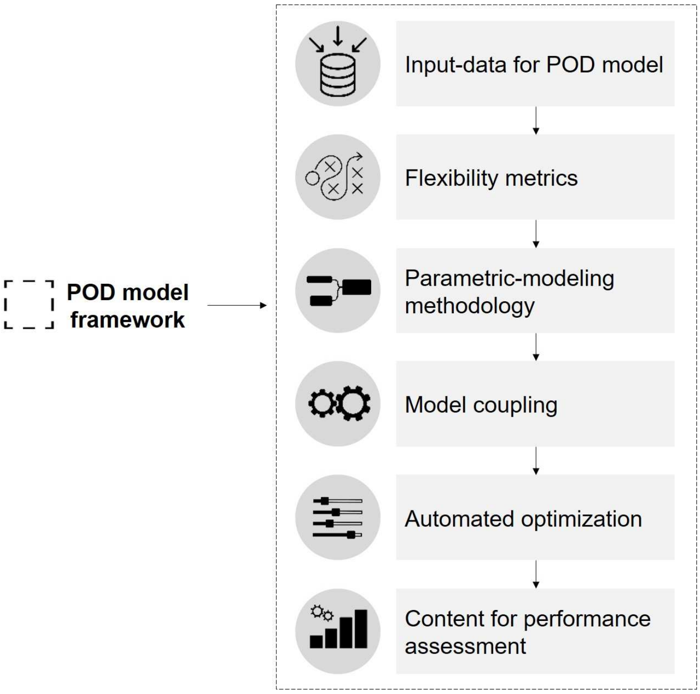

Figure 1: Research question and sub-questions

1.3 Research project BIMFlexi and scope of this doctoral thesis

This cumulative dissertation builds up on the research project “BIMFlexi: BIM-based digital platform to design and optimize flexible industrial buildings for industry 4.0”, which was funded by the Austrian Ministry for Transport, Innovation and Technology through the Austrian Research Promotion Agency (FFG, grant number: 877159, BRIDGE Program). The research project was conducted with the project partners from TU Wien - Institute of Visual Computing Human-Centered Technology, Buro DI Scheibenecker and Buro Jürgen Gaigg. Since the project is complex, interrelated, and conducted in an interdisciplinary manner, the broader framework and scope of the BIMFlexi project is briefly presented and the focus of this dissertation is emphasized (see Figure 2).

The primary goal of the research project BIMFlexi is to develop a Building Information Modeling (BIM)-based digital platform to design flexible industrial buildings that are efficiently adaptable to rapidly changing production processes, taking into account economic, ecological and technical parameters. The digital platform aims to integrate building and production planning processes and tools, couple digital planning methods (BIM, parametric design) with novel optimization methods and create an efficient visualization and decision support system with real-time feedback in Virtual Reality (VR). A computational parametric optimization and decision support (POD) framework with consistent data structuring of software-independent data (parameters, requirements, and cost functions) serves as background optimization process of building structures and production layouts and should enable real-time performance feedback and data transfer to Virtual Reality and BIM planning processes [26]. Thus, the parametric framework for processing is bi-directionally linked to a multi-user VR system for advanced visualization and user interaction for preference optimization and to BIM-based architectural, finite element methods and production planning tools for post-processing of generated designs. This thesis covers four peer-reviewed publications created during the conducted research within the BIMFlexi project, focusing on the aspects of an integrated parameter and requirement catalogue for flexible industrial building design, parametric performance based structural design integrating a method for production layout planning and integration of methods for real-time assessment of LCC, LCA, recycling potential and flexibility of building structures, meeting the requirements that arose during the course of the research project. Thus, in this dissertation the POD framework and the necessary input scheme and databases for optimization and real-time decision support are developed. The proposed framework excludes the development of the multi-objective algorithm for automated industrial building optimization, the multi-user VR platform and the coupling of the parametric framework to BIM-tools for post-processing.

The following section provides an overview of related work and state of the art in relevant research disciplines, in the areas of LCC, LCA, recycling potential and flexibility assessment as well as parametric performance based structural design, production layout planning and integrated industrial building design methods. Subsequently, a more detailed look at the doctoral thesis content is provided and the main part is structured in three parts: The first part focuses on the main objectives of the thesis. The second part is dedicated to describe the used methodology for workflow and design process development of the POD framework. The third part presents and summarizes the four scientific peer-reviewed publications. Finally, a conclusion is given and future steps are discussed.

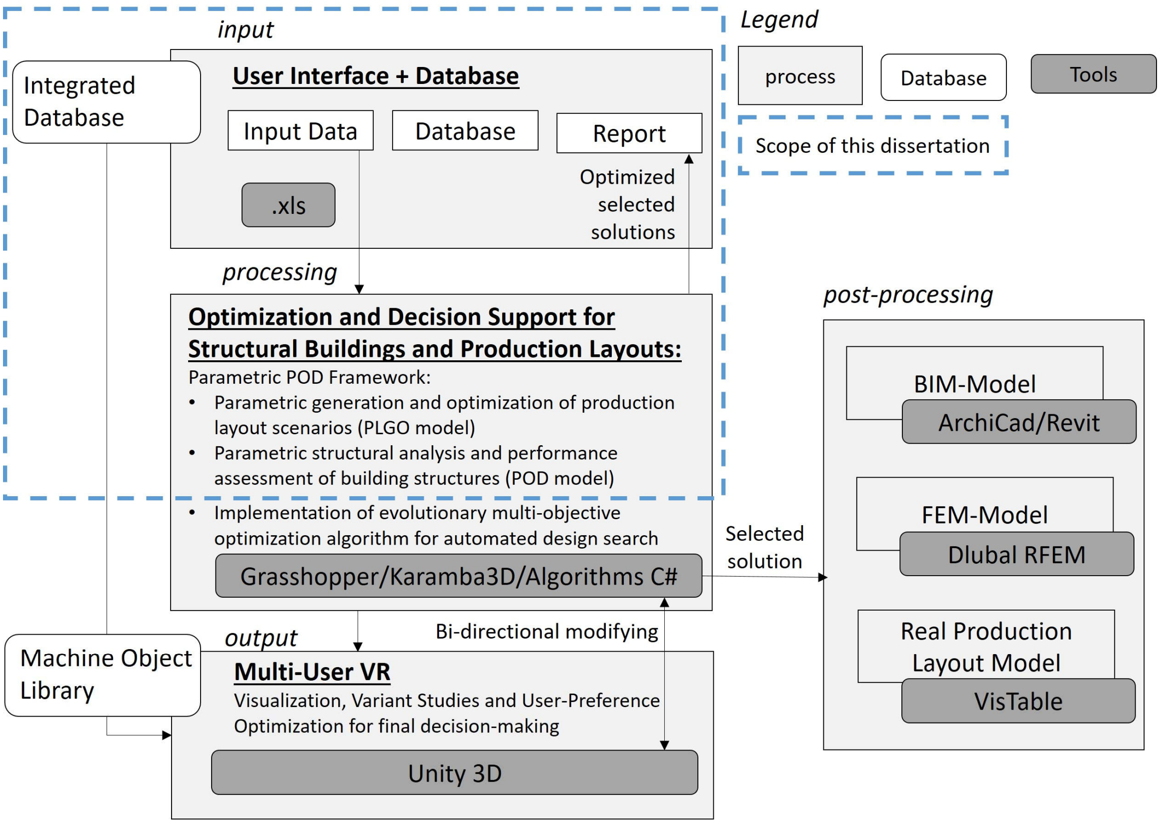

Figure 2: Framework of the digital platform of BIMFlexi and highlighted scope of this dissertation

2 State of the Art

This research is closely related to the topics of flexibility assessment, life cycle assessment, recycling potential assessment and life cycle cost analysis, as these methods have the common goal of improving the resource efficiency and durability of buildings, minimizing environmental impacts and costs. On the other hand, emerging parametric performance based design and optimization methods offer new opportunities for integrating, predicting and jointly optimizing building structures and production layouts. However, there is a lack of methods to link structural design and production planning for coherent performance improvement and early decision support in industrial building design. In the following, the relevant topics are presented and the state of the art in the literature is discussed.

2.1 Flexibility Assessment in Production and Industrial Building Design

Flexibility in building design is the ability of a space to adapt functionally or structurally to changes in use [27], while flexible production systems deal with uncertainties caused by demand changes, changes in user needs or new technologies and regulations [28]. In this dissertation, flexibility is defined as the ability of industrial building structures to adapt to the reconfiguration of production processes. Flexibility strategies can improve the sustainability of manufacturing processes [6] and buildings [29] and the whole life-cycle performance of production facilities that are subject to change [30]. Design strategies to increase a buildings' flexibility can consider three types: changes in the space functionality, changes in the load carried by the systems, and changes in the flow of people or environment [31]. According to Wiendahl, et al. [32], changeable manufacturing is characterized by the ability to anticipate and adapt structures and processes at all levels of a factory to impulses for change in an economical manner. The authors define five transformation enablers that can be used to achieve changeability in the design phase of production facilities: Universality, Scalability, Modularity, Mobility and Compatibility. A taxonomy and associated terminology for flexible architectural and engineering systems of production facilities is developed by Madson, et al. [8] and address the lack of flexibility guidance within production facilities. A joint consideration of manufacturing and industrial building flexibility for integrated industrial building design is rare and most identified flexibility metrics and concepts assess either the flexibility of residential buildings [23, 27, 33, 34] or in terms of production system process technology and operations management [35-37]. Geraedts [38] establishes an instrument to evaluate a building's adaptive capacity and defines flexibility key performance indicators based on site, structure, skin, facilities, and space plan division. A BIM (Building Information Modeling)-based parametric method for flexibility assessment of residential buildings is proposed by Cavalliere et al. [7]. A lack of flexibility metrics and a computational design method to quantitatively assess the flexibility of industrial building structures, taking into account changes in production processes has been identified.

2.2 Life cycle assessment (LCA) and recycling potential

Industrial businesses face increased pressure due to their environmental impacts and are challenged to minimize waste generation, resource scarcity, and sustain economic benefits [39]. A frequent method for assessing the environmental impacts of industrial buildings is LCA [22, 40]. LCA is an analysis method to examine environmental impacts throughout a building's life cycle from raw material extraction to production, use, and disposal and is set out in the international standard ISO 14040:2006 [41]. Various commercial LCA software are available such as SimaPro [42], Legep [43] or GaBi [44] Some LCA software provide data integration to BIM processes such as OneClickLCA [45] and Tally [46]. The online tool eco2soft [47] calculates a buildings environmental key indicators (Global Warming Potential (GWP), Acidification Potential (AP) and Primary Energy Intensity (PEI)). Eco2soft is based on the baubook calculator for building components [48] and the methodology provided by the Austrian Institute for Building and Ecology (IBO) [49].

Besides LCA, the determination of future recycling potential of buildings and elements should be included at early design stages for holistic environmental impact assessment. A few researchers consider the determination of the recycling potential of buildings [50-52] and Honic et al [50, 53] developed a method for a BIM-based Material Passport for buildings to evaluate the recycling potential and the environmental impact of materials embedded in buildings. A possible method to evaluate the recycling potential of buildings is according to IBO [54], the Austrian guideline to calculate the disposal indicator of construction and materials at building level. Thereby, the recycling potential can be determined with the online tool eco2soft, linking every material to a recycling grade ranging from 1 (very high recycling potential) to 5 (very low recycling potential).

2.3 Life cycle cost analysis (LCC)

Aside from the importance of the environmental impact, industrial buildings consume a significant amount of money for the construction cost, the cost of materials and supplies, and the maintenance and demolition of the building, which is important for the economic sustainability [1]. On international standard level, the life cycle costs of buildings are regulated by ISO 15686 [55]. The initial capital costs, the adaptation costs and the end of life costs need to be considered when calculating life cycle costs and can be determined by the net present value (NPV). Besides LCA, the software OneClickLCA provides a method for automated LCC calculation through import of building materials, quantities from Excel, BIM, or energy models [56]. Kovacic and Zoller [57] tested and compared the three LCC methods and tools from DGNB/BNB building certificate indicator 16:LCC [58, 59], ABK LEKOS Software [60] and Legep [43] for preliminary design of energy-efficient buildings and reveal that the tools are not suitable for the early design stage.

2.4 Production Layout Planning in Industrial Building Design

The production layout is the floor plan of the production facility, whereby an attempt is made to find the most effective workflow and best physical arrangement of machines, equipment and service departments for the production process. In practice, most for production layout planning methods are based on tasks involving manual assignments [61]. The automated solution of the physical organization of a production layout is challenging as it is related to many other components of the production plant and can be defined as facility layout problem (FLP). The FLP involves the allocation of tasks involved in the process in the best possible way, given multiple optimization criteria and constraints [62, 63]. Several FLP solving methods use a multi-objective evolutionary algorithm for automated creation and optimization of production layouts [62, 64]. The output is a block layout and most methods implement the two objectives of minimizing the material handling costs [65-67] and the total production time [68]. The generally used FLP optimization models have been subject to 18 different types of constraints, including: Area restrictions; non-overlapping of departments; number of material handling devices; budget; capacity; pick up/drop off locations; orientation and clearance between departments [69]. Most optimization methods for computational production layout design neglect building or flexibility-related objectives or constraints. Several researchers addressed the automated generation and allocation of architectural or space layout plans for building design [70-72] using evolutionary algorithms or parametric design methodologies [73]. While others developed methods which include a three-dimensional spatial zoning procedure for structural design [74] or generate structural system layouts for conceptual building spatial designs to assign structural components to a building spatial design geometry using response grammar and evolutionary algorithms [75]. Either researchers optimize space layout in building design or plant layouts of production systems, mutual consideration of production layout planning in structural building design has not been observed and is one aim of this thesis.

2.5 Parametric structural design for performance assessment and integration

To have a direct impact on building performance, design alternatives must be developed and evaluated at early design stages and integrated design approaches applied [51]. The level of detail and information in early design stages is low, requiring a high degree of abstraction when modeling a building, a challenge for integrated life cycle assessments [76]. As LCA requires high level of information and data, it is frequently used in late design stages, when all information about the building is already available, loosing early optimization potentials [77]. At early design stages, parametric and performance-based design methods, which are algorithmically based, offer interdisciplinary design teams the ability to integrate multiple disciplines for multi-objective optimization [78], include life cycle analysis [79, 80] and allow rapid exploration of vast design spaces with performance evaluation for decision support [14, 15]. Grasshopper for Rhino3D [81] is gaining popularity as visual programming language for parametric design and the Grasshopper plug-in Karamba3D [82] enables automated structural analysis of parametrically generated designs. Parametric design methods have been widely used by researchers in the field of architecture and structural engineering to optimize building geometries and/or energy and structural performance [14, 83, 84], however, rarely integrate LCC and LCA assessment methods besides structural optimization. OneClickLCA developed a plug-in for LCA assessment within Rhino and Grasshopper [81, 85] processes [86]. In addition, a number of other parametric LCA approaches have been developed such as Tortuga [87], CAALA [88] and Bombyx [89]. A parametric design process shows remarkable potential to support structural industrial building optimization in terms of LCC, LCA and recycling potential performance and to integrate production layout planning. However, most researches on sustainable industrial building design focus on the optimization of pre-defined building designs considering LCA [21, 22] or LCC [19] analysis separately. A holistic structural design-oriented exploration approach to improve the LCC, LCA and recycling potential of industrial building lifecycles at early design stage based on normative assessment frameworks and a strategy to integrate flexibility assessment and production layout planning in parametric structural design processes have to be explored.

2.6 Integrated Industrial Building Design

In this section, the state of the art and current research fields involving integrated design of industrial buildings and production systems is highlighted. In this dissertation, the term integrated industrial building design is used, referring to a holistic planning approach that combines building and production design disciplines and parameters simultaneously. However, several other terms i.e. integrated factory planning can be found in literature.

Researchers at RWTH Aachen University introduce the concept of “Condition Based Factory Planning” [90], thereby decomposing the factory planning process into standardized planning modules and introducing the concept of “Virtual Production Intelligence” to enable product, factory and machine planners to design products and production processes collaboratively. The result is an integrated information model that provides joint analysis of process characteristics to evaluate planning scenarios in advance and to increase production quality, efficiency and decision support [18, 91]. Research at TU Braunschweig developed an application-oriented, validated methodology in form of a planning guide for holistic integration and optimization of the planning and realization process for future-oriented and sustainable industrial buildings. A “Life Cycle Engineering” tool was developed to evaluate sustainability of industrial projects [92]. Other researches examine the possibility of BIM for integrated factory planning of manufacturing and construction systems, revealing poor realization in factory planning projects due to lack of maturity specifications and data management standards [9]. Furthermore, the potential of ontologies for automated design validation in BIM-based factory planning approaches, including technical service equipment and production design, to improve the collaboration efficiency and reduce the need of human interference is examined [17]. At TU Dortmund researchers from the research training group “Adaptation Intelligence of Factories in Dynamic and Complex Environments” develop an automated BIM-based decision support method and focus on the technical transformability of the factory building using BIM [16]. A hybrid modular planning approach is presented, synchronizing factory and building planning through a component based synthesis [93]. Delbrügger, et al. [94] presented a framework for an unified navigation approach that combines BIM models with dynamic interior features, the exterior environment, and different types of motion. The research project “BAMA Balanced Manufacturing” investigated simulation-based methods to monitor, predict and optimize the energy and resource demand of production companies. Thereby, a method for real-time aggregation of a product footprint during manufacturing is developed, which addresses the impact assessment in terms of the dynamic carbon footprint, neglecting the static carbon footprint of the building [95]. On production building side, the potentials and deficits for modelling, analyzing and optimizing the energy- efficiency of industrial buildings using BIM are explored [5].

There have been valuable research efforts to improve collaboration in industrial building design and production planning and to develop integrated computational tools and simulation strategies, however, these efforts have not yet provided solutions to consider the influences of changing production processes that may occur during the life cycle in the early structural design of industrial buildings. Isolated systems for parametric LCC/LCA assessment or parametric structural design optimization methods exist. The identified research gaps remain in an integrated design and decision support methodology to optimize the resource efficiency of industrial buildings in the early design stage, taking into account production layout planning with automated economic, environmental and flexibility performance feedback. The state of the art analysis reveals that new digital design methods need to be explored for simultaneous evaluation and integration of production layouts into structural design, and a flexibility assessment method for industrial building design has to be defined.

3 Objectives

The objective of this doctoral thesis is to provide an integrated industrial building design method for the design and optimization of flexible load-bearing structures that consider dynamic production processes already at early design stage. The overall goal is to improve the resource efficiency and life cycle of industrial buildings in long term. Hence, this doctoral thesis establishes a parametric optimization and decision support (POD) model framework for simultaneous LCC, LCA, recycling potential and flexibility assessment of industrial building structures incorporating production planning. The main objective can be broken down into its most important sub-objectives (see Figure 3):

- Design space development for integrated industrial building design
- Definition of flexibility metrics for industrial building design

- Parametric method for integrated production layout planning
- Development of the POD framework for integrated performance improvement

3.1 Design space development for integrated industrial building design

For the realization of the main aim, which is the development of a computational design and optimization method for flexible industrial building structures that integrates production planning requirements, the conceptual design space exploration scheme must be defined. The first objective is to define a unified design space representation for parametric design space exploration in integrated industrial building design, respecting both building and production requirements. For an efficient design space representation, the design variables, the constraints and the objectives of the industrial building and integrated production model must be defined in order to be able to consider the most important contents, elements, loads and materials during the parametric design search. The design space representation serves as basis for the development of the parametric performance-based design methodology. This research focuses primarily on the conceptual and early design stages of structural design and production layout planning and the modeling methodology needs to be defined according to these levels of abstraction. A further aim is to determine the economic and environmental indicators that should be included in the POD framework for structural performance assessment and decision support. A major goal is to evaluate the flexibility of the building structures and layout, however, there are no uniform flexibility metrics for industrial buildings. Hence, the definition and derivation of flexibility metrics for the evaluation of industrial buildings and related production is the second sub-objective of this thesis.

3.2 Definition of flexibility metrics for industrial building design

A number of standardized methods and indicator definitions that promote a whole-building approach to sustainability (e.g. energy efficiency, water efficiency, cost efficiency, waste efficiency…) exist. However, there is a lack of approaches to define and assess a systems flexibility, especially in the design of industrial buildings, taking into account building and production criteria. The objective is to define flexibility metrics for integrated industrial building design and implement them in the computational model in order to optimize the flexibility of industrial building structures with respect to changing manufacturing conditions. Flexibility metrics have to be formulated mathematically according to the defined variables of the design space representation to obtain measurable values for evaluating the flexibility of structures and production layouts.

3.3 Parametric method for integrated production layout planning

Production and industrial building design processes run sequential, neglect discipline-specific interaction, and design and simulation models often lack interoperability. An integrated industrial building design approach, in which building and production systems and components are coordinated, is one of the major aims of this thesis. An important basis for the realization of flexible industrial buildings is to consider the material, production and media flows of the layout design. The goal is to develop the design space for a production layout generation and optimization model that integrates building and flexibility criteria based on parametric modelling. The resulting parametric production layout method must produce different changeable layout scenarios that can be considered in the parametric structural design process. The formalization of the design space and the objectives need to be based on the defined design space for integrated industrial building design. The developed production layout method should be applicable not only by production planners, but also by architects and engineers to quickly and independently create production layout scenarios for building simulations and variant studies.

3.4 Development of the POD framework for performance assessment

The main objective of this thesis is to establish an integrated optimization and decision support framework that enables the design of flexible building structures considering production layout scenarios. The aim is to improve industrial buildings resource efficiency by providing environmental and economic feedback on design decisions already at early design stage. To minimize the costs, carbon footprint and waste contribution of industrial building structures the developed framework aims to enable automated LCC, LCA and recycling potential assessment of building structures. In order to influence and increase the life span of industrial buildings, the framework intends to integrate the methods for production layout planning and flexibility assessment directly into the parametric structural design process. The developed methodology targets to enable design teams to conduct rapid variant studies to compare the performance of building alternatives thus to improve decision-making. Parametric tool chains and environmental and economic databases are investigated and developed regarding their interfaces as well as their applicability for the POD framework. The POD framework must be generated based on the developed design space structures and defined objectives. Based on individual subsystems and required data, a holistic workflow for the POD model and the coupling, process and handling need to be defined.

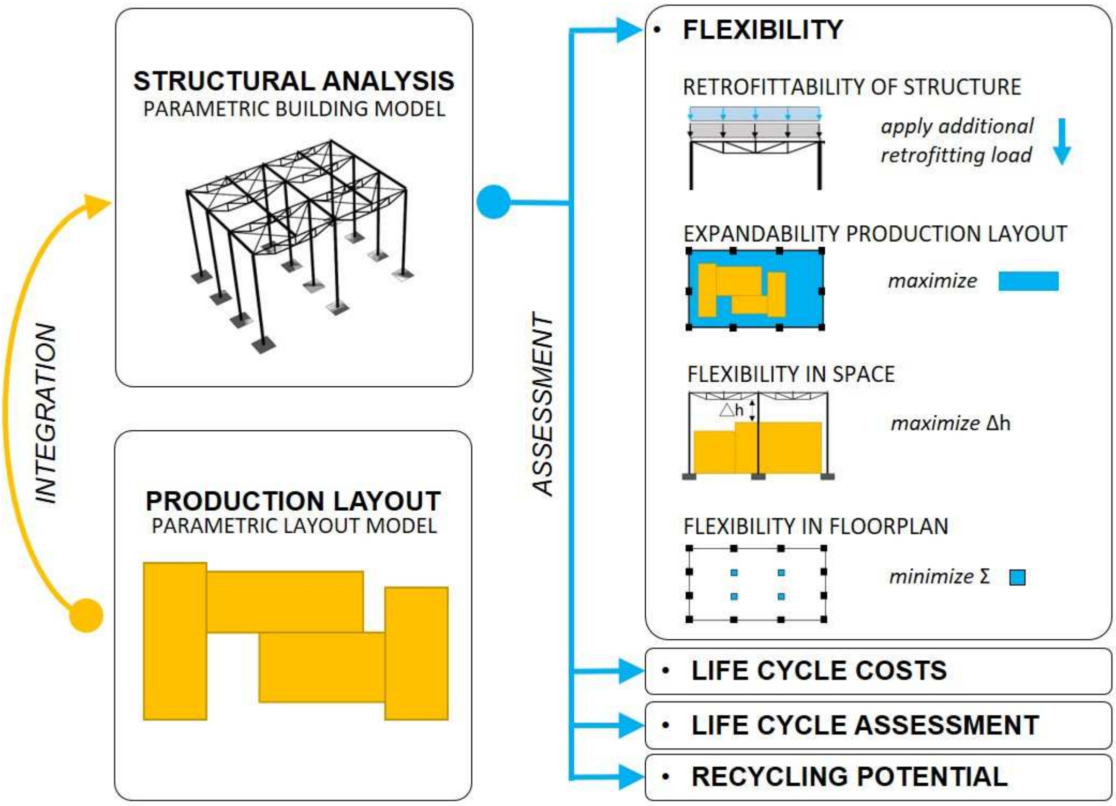

Figure 3: Objectives of this thesis and developed POD framework

4 Methodology

This dissertation develops a parametric performance-based design process for industrial buildings that incorporates production planning to evaluate and optimize the flexibility and economic and environmental impacts of industrial building structures at early design stage. The methodology used to create the POD framework is based on parametric modelling, multi-objective optimization methods, and methods for life cycle analysis. For improved decision support, a novel method for grading and comparing of generated building variants is developed to support design decisions towards sustainable development. In addition, the proposed framework serves as an integration platform for industrial building design with the potential to implement other discipline-specific tools and simulations such as energy efficiency assessments in the future.

The research has been conducted by the following steps: Basic research through expert interviews and a state of the art analysis was conducted to investigate the discipline-specific critical parameters, methods, models and processes of building and production planning. The qualitative research was supplemented with a comprehensive use-case study to identify crucial discipline-specific elements and analyse interdependencies from building topology and production systems. Based on the collected knowledge and data, the design space representation and a concept of integrated production cubes for integrated industrial building design was developed and a method for flexibility assessment of industrial building structures defined. The design space was translated into a POD model through parametric modelling. To enable the integration of production planning in the design process, a suitable parametric methodology for automated production layout generation and multi-objective optimization (PLGO) was developed. The POD model and the PLGO model are coupled into the holistic POD framework. The framework is complemented by two methods to improve decision support: an integrated automated method for economic and environmental impact assessment of building structures and a novel grading system for transparent evaluation and comparison of building variants. The POD framework represents the main contribution of this dissertation and is tested on a pilot project from a food and hygiene production in Austria.

4.1 Design space development and integrated production cubes concept

An exploratory multiple case study according to Yin [96] was conducted to gain in-depth knowledge of the integrated design of industrial buildings and to become aware of the differences and similarities between different production facility projects. As part of the case study methodology, 15 experts (building owners, architects, structural engineers and production planner) were interviewed and a use case study of 29 representative real industrial building projects from Automotive, Food and Hygiene, Logistics, Metal processing and Special production was conducted. Within the use case study, the projects were analysed by means of drawings, technical reports and digital models from architectural, structural, technical building service and production planning to identify functional and technical discipline-specific interdependencies, to define relevant elements and parameters for the design space and to collect concrete data values and ranges for variables and constraints for the parametric model. The information obtained from the expert interviews allowed to gather discipline-specific knowledge about relevant technical parameters to be integrated into the framework, and to identify priorities, potentials and problems in industrial building design processes. The collected data from the multiple case study was finally supplemented by information gained from a state of the art analysis to develop the design space and the parametric model framework. To achieve integration of building and production planning, a concept of integrated production cubes was developed. The concept is adapted from Smolek et al [95], where the production plant system is divided into modules, so-called "cubes", from an energy perspective. In this research, the idea of defining the production process in production cubes was adopted, whereby a production cube is a rectangular, orthogonal volume described by its dimensions in x-, y- and z- direction. Each cube is assigned to a specific production process type and describes a sub-process such as milling, storage etc.. One cube contains the dimension and load requirements from the machines, working area around the machine and the maintenance area and media supply of a sub-process. The total production area layout is the sum of the area of all production cubes. The cubes with its load and geometry requirements are integrated in the building model and respected in structural design. For reasons of modelling simplicity, computational time, and tool handling, it was more beneficial to develop the production layout model and the building model in two separate parametric models which are subsequently coupled in the parametric design process, see section 4.3.

Variables considered as input parameters in the design space for the building model:

- Horizontal and vertical modularity: Axis grid dimension and number of axis fields in primary (x-) and secondary (y-) direction and inner hall height (z-direction)
- Load-bearing structure type (x- and y-direction): Steel framework, Steel girder, Precast concrete T-girder, Timber girder and Timber framework
- Column type: Reinforced concrete quadratic and Steel HEM profile
- Bracing type: Bracing of wall and roof in x- and y-direction
- Load Case type: Application of a retrofit load for future adaptability of the structure

Variables considered as input parameters in the design space for the production model:

- Production process type: Procurement, Production/Assembly, Distribution
- Sub-process: Definition of production cubes (x-, y-, and z-dimension and expected loads and geometry requirements from machines and media supply)
- Process definition: Lean-factor matrix and Transport-intensity matrix

4.2 Objectives and flexibility metrics for decision making

The results from the multiple case study and the literature review revealed the relevant objectives and parameters to be integrated in the framework for flexible and sustainable structural design and production planning. Figure 4 presents the implemented objectives for multi-objective optimization of the PLGO model and the performance assessment objectives of the POD model for decision support.

The production layout model aims to maximize the flexibility of production layouts within the building and the process productivity. The five objectives for production layout optimization can be summed up as:

- Flexibility: Free building area, Layout density, Cube dimension ratio
- Productivity: Lean-factor matrix, Transport-intensity matrix

The industrial building model aims to improve the economic and environmental impact and flexibility of the building structures. The ten objectives for structural performance assessment can be summed up as:

- Economic impacts: LCC
- Environmental impacts: GWP, AP, PEI, PEIn, and Recycling rate of the building
- Flexibility metrics: Retrofittability of structure, Expandability of production layout, Flexibility in space, Flexibility in floor plan

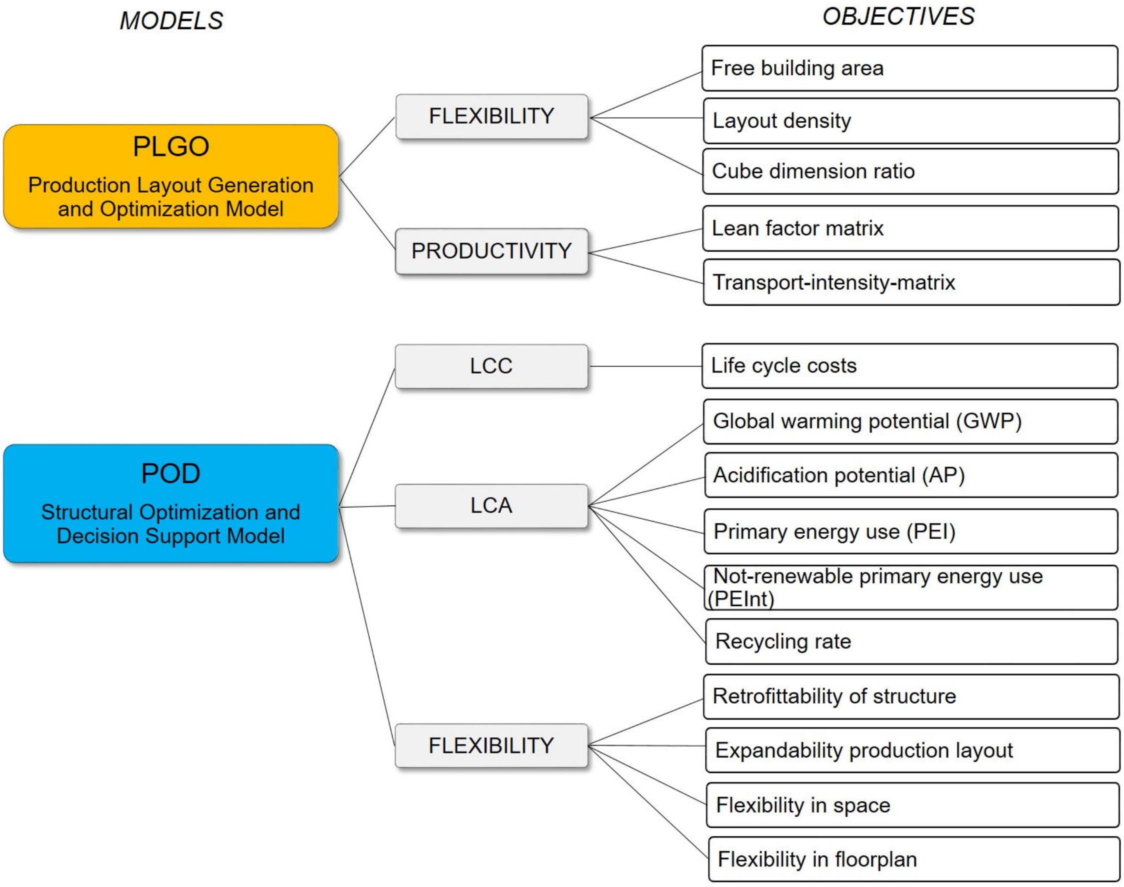

Figure 4: Detailed overview of implemented objectives in the POD framework

As there is a lack of common flexibility assessment methods in industrial building design, four novel flexibility metrics based on the results of the expert interviews, literature review and use case study were developed (as shown in Figure 3) and a method for assessment of these metrics implemented in the POD model as presented in the second research paper of this cumulative dissertation. The determination of relevant indicators for the economic and environmental performance assessment is gathered from existing databases. For the assessment of the LCC, the data from the German construction cost indices - BKI [97] and for LCA and Recycling potential assessment the data from the Austrian database baubook.at [48] was acquired and implemented in an excel-based repository. In this research, the implemented LCC-methodology is based on the net present value (NPV) calculation according to ISO 15686-5 [55], the LCA-methodology is based on IBO, the Austrian Institute for Building and Ecology [49] and the recycling potential methodology is based on the Austrian guideline for calculating the disposal indicator of building components by IBO [54]. The LCC, LCA and recycling potential assessment methods are directly integrated into the POD model, where result calculation is conducted. The LCA assesses the environmental impacts of GWP (Global Warming Potential), AP (Acidification Potential), Primary Energy Intensity Renewable and Non-Renewable (PEI and PEIn) of building structures and enclosure systems. The focus of the research is on improving the resource efficiency of buildings, and therefore only embodied energy was evaluated, neglecting operational energy.

4.3 Parametric workflow and design process for the POD framework

Parametric methods, computational tool chains, and ecological and economic databases were investigated and developed with respect to their interfaces as well as their applicability for the POD framework. The POD framework is built based on the defined parametric building and production design spaces and models, the methods for LCC, LCA, recycling potential and flexibility performance assessment as well as a grading system method for multidisciplinary decision support. Thus, the proposed framework can be considered as a set of interacting subsystems. Based on the individual subsystems and required data, a holistic workflow for the POD framework was developed (see Figure 5). The visual programming tool Grasshopper for Rhino3D [81] is used to create both parametric models, the PLGO model for production layout scenarios generation and optimization and the POD model for structural analysis and performance assessment. The PLGO model provides a method for automated generation and multi-objective optimization of production layout scenarios through integration of an evolutionary algorithm into the parametric model. The parametric structure is based on the developed integrated production cubes concept and the algorithm produces layout scenarios with quantitative performance feedback which can be integrated in the structural design process. The POD model enables automated structural analysis with parallel LCC, LCA, recycling potential and flexibility assessment. For the structural analysis and automated dimensioning of the structural elements the POD Grasshopper model is enriched with Karamba3D [98] components. The methods for LCC, LCA and recycling potential assessment, as described in section 4.2, are implemented in the visual programming environment to enable simultaneous performance assessment of the building structures. The specific indicators for the economic and environmental performance assessment are stored in a repository that is coupled to the POD model. A grading system method for decision support is implemented in the POD framework to enable evaluation and comparison of generated building variants based on their performance results. The structure of the grading system is presented in section 5 (Paper 4) and is based on methods applied in the DGNB system

[99]. The production layouts, building structures and performance results are visualized in Rhinoceros 7 [85] and in the grading system mask.

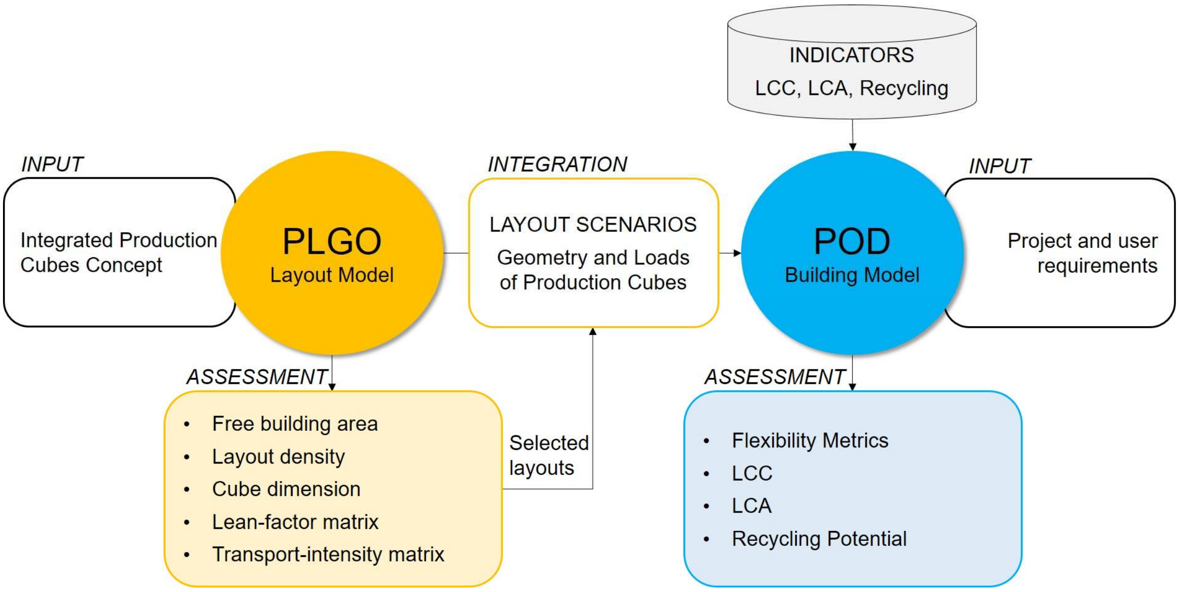

Figure 5: POD framework for decision support in integrated industrial building design

The integrated design process, the coupling of the POD and PLGO model and the handling of the POD framework for variant studies and decision support is illustrated in Figure 6. In the workflow of the POD framework, the selection of layout scenarios which are intended by the users to be respected in the building design process is semi-automated. Designers select preferred layout scenarios from the PLGO model according to the fitness rating and visualized layouts. This manual interaction is intended, as it enables the involvement of the designer's knowledge in the design process, rather than relying just on the best rated scenarios produced by the algorithm. The PLGO and POD model methods are developed that they could be used as independent design and optimization tools. However, in order to achieve integration, the models are coupled, thus a methodology is created to respect production layout scenarios and their geometrical and load requirements in the structural design process. The data exchange from the PLGO model to the POD model is ensured by an excel-based requirement specification and database, which also integrates the grading system method for final decision support.
The developed parametric framework for structural industrial building optimization and the defined quantitative flexibility assessment metrics are tested on a pilot-project of a food and hygiene production facility from Austria (use case 1). The PLGO framework is tested and evaluated on a pilot-project of a hygiene production facility from Austria (use case 2). The final proof of concept of the POD framework is conducted on use case 1.

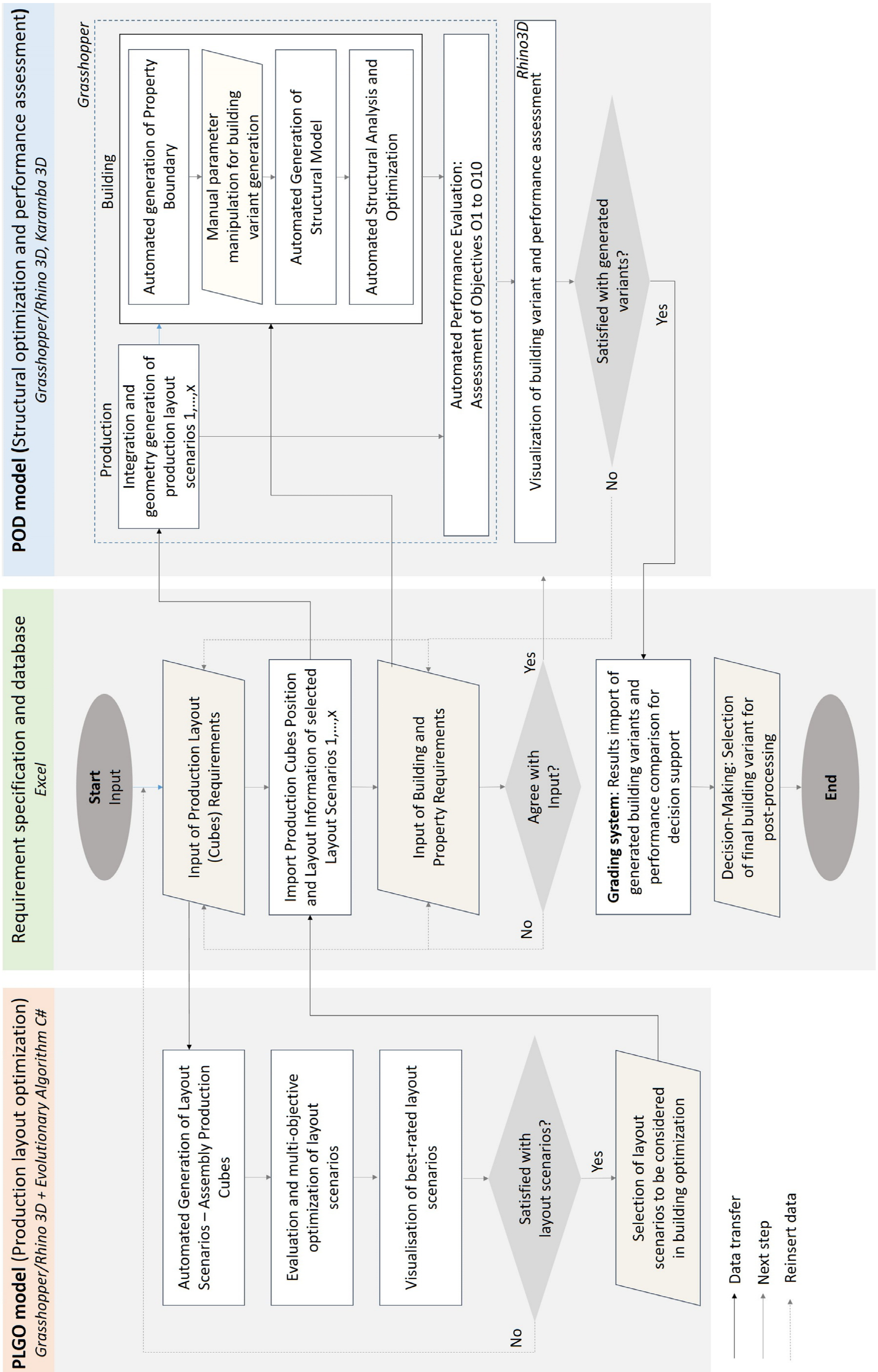

Figure 6: Design process and model coupling within the POD framework.

5 Results

The research conducted as part of the doctoral thesis is documented in four scientific peer-reviewed papers and is structured as follows:

The first paper (**P1**), presents the systematic **design guideline for flexible industrial buildings towards the requirements of industry 4.0** by means of a categorized parameter catalogue to identify the necessary input and content of the parametric model. The second paper (**P2**) presents the developed **parametric design process for design space exploration and flexibility assessment in integrated industrial building design.** The developed parametric framework for automated structural building optimization and defined quantitative flexibility assessment metrics are tested on a pilot-project of a food and hygiene production facility (use case 1), in order to evaluate the design space representation and validate the flexibility metrics. The third paper (**P3**) introduces the **parametric evolutionary design method for automated production layout generation and optimization** (PLGO) for the implementation into the parametric building design process from P2. The PLGO framework is tested and evaluated on a pilot-project of a hygiene production facility (use case 2) to validate the defined constraints and objectives. The fourth paper (**P4**) integrates the parametric models of P2 and P3 into the holistic **parametric optimization and decision support (POD) model framework** that enables structural analysis and element dimensioning with quantitative flexibility rating, accommodating a selection of several prioritized production layouts in early industrial building design. The framework integrates the method for automated LCC, LCA and recycling potential assessment for extended performance assessment of generated industrial building structures. In addition, a novel grading system is introduced and implemented that enables holistic assessment and comparison of building design variants for improved decision-making support to guide design decisions towards economic and environmental sustainable industrial buildings. P4 is also representing the **proof of concept** for the developed workflow, testing the framework on use case 1.

The focus areas and associated research papers of this thesis are presented in Figure 7.

- **P1** Julia Reisinger, Patrick Hollinsky and Iva Kovacic:
  “Design Guideline for Flexible Industrial Buildings Integrating Industry 4.0 Parameters.” *Sustainability* (2021).

- **P2** Julia Reisinger, Maximilian Knoll and Iva Kovacic:
  “Design space exploration for flexibility assessment and decision making support in integrated industrial building design.” *Optimization and Engineering* (2021).

- **P3** Julia Reisinger, Maria Antonia Zahlbruckner, Iva Kovacic, Peter Kán, Xi Wang-Sukalia and Hannes Kaufmann:
  “Integrated multi-objective evolutionary optimization of production layout scenarios for parametric structural design of flexible industrial buildings.” *Journal of Building Engineering* (2022).

- **P4** Julia Reisinger, Stefan Kugler, Iva Kovacic and Maximilian Knoll:
  "Parametric Optimization and Decision Support Model Framework for Life Cycle Cost Analysis and Life Cycle Assessment of Flexible Industrial Building Structures Integrating Production Planning" *Buildings* (2022).

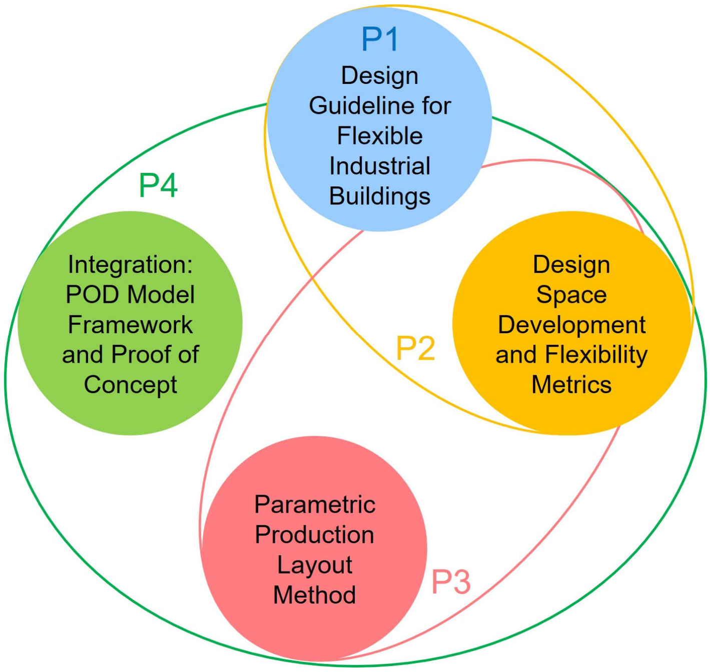

Figure 7: The focus areas and associated research articles of this thesis

5.1 Summary of research papers

The first paper (**P1**) gives an overview about the current design and construction practice of industrial building and production systems and presents relevant parameters and processes in integrated industrial building design practice, taking a first step to answer RQ1 and RQ2. A definition and description of the relevant discipline-specific objectives, parameters, requirements and processes was necessary at the beginning of the research in order to define the design space representation presented in the second paper (P2) and the requirements for the parametric integrated production layout planning method developed in the third paper (P3). Therefore, this paper addresses the lack of a holistic design guideline for flexible industrial buildings integrating requirements of Industry 4.0 by collecting and incorporating parameters of production and building planning in the form of a categorized parameter catalogue. The methodology for the parameter collection employed literature review and expert interviews based on a multiple case study to determine objectives, technical parameters, and demands on the planning process in integrated industrial building design. According to a content analysis of the expert statements, the specific parameters are classified into success factors, suggestions for improvement and deficits in current design practice. Results show that flexibility was identified as primary goal in integrated industrial building design which includes parameters such as reconfigurable machine layouts and production expansion areas, maximum free gross floor area of the building, maximum span width of girder constructions for column-free zones, a maximum inner hall height, and maximum production process variability. On technical parameter level, structural design and production planning criteria were defined as crucial success factors, as the load-bearing structure and production systems having a high impact on flexibility. Structural design-related technical parameters are the type of material and load-bearing system, the dimensioning and position of the structural elements as well as increased load-bearing capacity through over dimensioning of elements to allow future changes in use. Success factors on planning process level were identified in the context of focusing on the early design stage and integrated design, containing parameters such as early integration of structural design and different production process scenarios, efficient interfaces amongst different disciplines on process and model level, technological innovation integration and standardized exchange formats within a common digital language. The results presented in this paper provide the rationale for the need of an optimization and decision support model for the early design stage of industrial building structures that integrates flexibility criteria and production planning requirements. It provides a conceptual modeling guide for the research presented in P2 and P3 and serves as a justification for the practical use of the POD framework (P4).

The second paper (**P2)** deals with the development of a concrete design space and the definition of parameter and numeric flexibility metrics for sufficient design exploration in integrated industrial building design. Based on the results of P1 and by means of a comprehensive state of the art analysis and an explorative multiple case study, holistic data from architectural, structural, technical building service and production planning are collected and discipline-specific parameter interdependencies are analyzed, resulting in a unified design space representation for integrated industrial building design. Based on these results, P2 presents the developed parametric design and decision support model (POD model), integrating a performance-based structural optimization process and a method for integration of production planning by means of a production cubes assembly scheme, answering RQ1. The framework consists of the seven concrete steps of: (1) Production input, (2) Structural input, (3) Automated building geometry generation, (4) Structural elements definition, (5) Structural analysis, (6) Structural performance & dimensioning and (7) Flexibility and net costs assessment. First, the "structural system grid" is established by the building's primary dimensions and structural elements, which are characterized by vectors, variables, and structural element types. In order to be able to consider production planning in the structural building optimization, the production process is described in form of the arrangement of so-called "production cubes". A production cube is described by variables of its outer geometries (width, length, height) and always relates to a single sub-process such as storage, conveying or milling. The sum of all production cubes represents the production layout. In P3, the production cube concept from P2 is adopted and further refined to a novel parametric method for automated production layout generation and optimization. P2 also addresses the lack of a uniform flexibility assessment definition in industrial building design and presents four novel flexibility metrics, respecting both manufacturing and industrial building criteria. The defined flexibility metrics relate to the retrofittability of the load-bearing structure, expandability of the production layout, the building’s flexibility in space and the building’s flexibility in floor plan. The automated calculation of the flexibility metrics is implemented in the parametric design process, giving real-time feedback on the flexibility of different building design options. The parametric design process is tested and the flexibility metrics are validated on a pilot-project of a food and hygiene production facility (use case 1). The test case confirmed the efficiency of the process for design exploration of industrial building structures for decision support as well as the accuracy of the flexibility metrics examined in trade-off with the net cost of the load-bearing structure. The parametric framework presented in P2 serves as the POD model in the POD framework, to which all other components are linked, as presented in P4.

P3 deals with the lack of a production layout planning and optimization method that can be integrated in building design processes. In P3 a method is investigated to integrate production layout planning directly into the parametric building design process as presented in P2 and answers RQ1. A parametric evolutionary design method for automated production layout generation and optimization (PLGO) is presented. The methodology is based on a state of the art analysis and an explorative multiple case study to define the design space and develop a novel integrated production cube concept as basis for the parametric PLGO framework. A multi-objective evolutionary algorithm, which was developed by the project partners from TU Wien - Institute of Visual Computing Human-Centered Technology, is implemented in the PLGO framework. The algorithm automates the production layout design search and considers building design and flexibility criteria. The presented evolutionary parametric design process and the implemented objectives and constraints follow the recommendations of the design guideline for integrated industrial building design (P1) and the parametric structure and the production cubes concept (P2). The evolved integrated production cubes concept in P3 describes the geometrical description and spatial arrangement of the production cubes, following the definitions presented in P2. The production process and material flow is determined by the spatial arrangement, functional sequence and dependencies of the production cubes, which is taken into account in the optimization using the relational lean factor matrix and the transport intensity matrix. Based on the integrated production cube concept, the PLGO framework is developed, respecting five constraints and five objectives for the evolutionary optimization to evaluate the cubes' positioning, interrelation and geometry. The algorithm integrates production and building related design objectives and optimizes the production layout scenarios based on the trade-offs productivity (maximize lean-factor matrix rating, minimize transport-intensity matrix) and building flexibility (maximize free building area, maximize layout density and minimize cubes' dimension ratio). The framework enables rapid multidisciplinary decision support by providing design teams with quick quantitative and visual feedback on production layout scenarios based on production and building related input and output requirements. The PLGO framework is tested on a real project of a hygiene production facility (use case 2). A sensitivity analysis of the objectives and constraints and a PLGO framework test is performed to evaluate and validate the suitability of the integrated production cubes concept, the parametric PLGO framework and the defined constraints and objectives. The conducted test case showed that the parametric design process for production layout planning produces feasible production layouts that respect flexibility and building criteria. The generated production layout scenarios create viable results for integration and investigation in the parametric structural design process from P2. The PLGO framework from P3 is an essential subsystem of the POD framework (P4).

The fourth research paper (**P4**) answers RQ2 as it is a combination and extension of all achieved aims from P1 to P3 and the final result of this dissertation, showing the content, structure and models of the POD framework for an integrated industrial building design process, enabling flexible and sustainable buildings. The parametric models from P2 and P3 are coupled in the POD framework. Moreover, the POD model from P2 is extended by a method for automated enclosure construction (roof, walls, and floors) assessment and a methodology for simultaneous performance assessment of LCC, LCA, recycling potential and flexibility of the building structures. A grading system for decision support is presented to enable evaluation and comparison of generated building variants based on their performance results. Furthermore, the paper provides a detailed description of the implemented objectives. The POD framework can be conceived as a set of interacting subsystems and is based on an industrial building component library and requirement specification, an ecological and economic indicator repository, the integration of the PLGO model (P3) into the POD model from P2, the extension of the POD model with an additional enclosure system assessment method and a method for economic and environmental impact assessment of building structures. A grading and result visualization system for efficient variant comparison to improve the decision support complements the framework. The presented POD framework enables automated structural analysis with quantitative real-time feedback to LCC, LCA, recycling potential and flexibility, respecting multiple changing production layout scenarios in the design search. Through this paper, the proof of concept of the developed parametric workflow is given. The framework was tested on a pilot project from a food and hygiene production facility from Austria (use case 1). The initial building design of the pilot project is compared with several generic designs to validate the calculation results and evaluate if the framework has the potential to identify savings in the economic and environmental impacts of industrial building structures at early design stage. The test case shows the usefulness of the framework for informed decision making at early design stage, to carry out quick variant studies and to efficiently compare different alternative building materials and low-impact structural systems that interdisciplinary designers can better understand the implications of their design decisions on the production layout and structural building performance. The POD framework and the proposed objectives from P4 are the final result of this doctoral thesis. The proposed developments serve as the basis for future research in BIMFlexi, where an evolutionary multi-objective optimization algorithm will be developed and implemented in the POD model to automate the building design exploration process.

6 Conclusion

The design of flexible industrial buildings that take dynamic manufacturing processes into account is crucial for sustainable development. In the early stages of industrial building design, an effective integrated decision support approach that links structural design and production planning is essential to enable designers efficiently evaluating, optimizing and finding flexible building structures. This dissertation closes the research gap of an integrated design process for joint planning of production layouts and load-bearing structures and the lack of a flexibility assessment method for industrial building structures. The developed POD framework for integrated design and optimization of economical, environmentally friendly, and flexible industrial buildings proposes a parametric approach that couples production planning and structural building design processes and provides a method for automated structural performance optimization with simultaneous LCC, LCA, recycling potential and flexibility assessment. The POD framework helps designers to make sustainable design decisions to obtain better industrial building solutions. A new method is offered to integrate, predict, and jointly optimize industrial building structures and production layouts towards maximum flexibility. The POD framework can be seen as an important instrument for the integration and collaboration of interdisciplinary teams at early design stage as it provides a transparent foundation for decision makers to not only follow their own design rules, yet to understand the impact of underlying design decisions on the overall economic and environmental building performance.

The first research question (RQ1) on how to integrate production planning and structural design processes, could be answered with the definition of the parametric design approach and its implemented integrated production cubes concept, enabling to consider building related information in production planning and dynamic production processes in structural design. The integrated parametric design approach is based on the joint definition of building and production related parameter (presented in P1) and the development of the parametric structural design process for sufficient design exploration in integrated industrial building design (presented in P2). The developed PLGO model (presented in P3) for parametric production layout generation and optimization can be directly integrated into the parametric structural design process of the POD model and is a method for quantitative evaluation, visualization, and comparison of generated layouts to avoid manual iteration steps in integrated design practice.

The second research question (RQ2) could first be answered by the development of the design guideline for flexible industrial buildings integrating production planning requirements as presented in P1, describing the relevant discipline-specific objectives, parameters, requirements and processes for efficient integrated industrial building design practice. The design guideline in form of a categorized parameter catalogue captured the complex industrial building design process and provides theoretical support to designers. Four novel flexibility metrics were defined and directly implemented in the POD model to assess the flexibility of the load-bearing structure with respect to changing production layouts (presented in P2). Accordingly, the developed POD framework (presented in P4), coupling the POD model and PLGO model, and integrating a method for simultaneous assessment of LCC, LCA, recycling potential, and flexibility performance of building structures and enclosure systems, enabled to provide the framework for a structural optimization and decision support method to design sustainable and flexible industrial buildings at early design stage. The POD framework presents an integrated industrial building design process and creates common interfaces and data structures for bi-directional data and information exchange along the value chain of production planning and structural building design.

Prior research on integrated design of factories suggest the potential of BIM-related tools for integrating manufacturing and building design, yet point to the lack of heterogeneous data and interoperability of discipline-specific models [9, 17, 18]. Various researcher assess sustainability of industrial buildings [21, 22], however, neglect to incorporate flexibility. This doctoral thesis contributes to research on flexibility measurements in building and production planning [6-8] as it introduces quantitative flexibility metrics for integrated industrial building design, which respect architectural, structural, media supply and production requirements. By defining and integrating flexibility assessment metrics into the production layout planning and structural design process, this research is an important milestone in raising awareness of the importance of flexibility to extend the service life and thereby the sustainability of buildings. Hence, this thesis differs from previous research on industrial building and production planning as it analyzes the discipline-specific data and interdependencies of building owners, architects, structural engineers, and production planners and integrates them into a parametric performance based design framework for early decision making.

The innovative contribution of this dissertation is that design teams can coherently analyze, visualize, and compare production layout and industrial building variants in the early design stage, reducing the danger of physical collision with the building structure. Modified production layouts can be considered in structural design, collision checks can be performed, and multiple manual processing steps can be minimized. The obtained results are of great practical importance as building owners, production companies, architects and engineers can efficiently visualize the complex interdisciplinary aspects around industrial building design processes including production planning processes. A method is provided that interdisciplinary designer can understand the overlapping impact of changing production processes on the economic and environmental lifecycle footprint of building structures to improve the resource efficiency and durability of industrial buildings already at early design stage. However, some research gaps and limitations for practical implementation remain:

The POD framework can be seen as an agile integration platform for the design of industrial buildings, which has the potential to be expanded with additional discipline-specific tools and simulations in addition to structural design. This research has mainly been focused on resource efficiency optimization, however, lacks to integrate energy planning specific models and simulations. Since energy efficiency and optimization of operational energy are major topics for sustainable development in industrial building design, energy aspects need to be integrated in future research.

The proposed design process of the POD framework is semi-automated, as it requires human interaction on both, production and building side. This is explicitly intended in order to incorporate the designer's knowledge and give freedom regarding selection of desired production layout scenarios, thus not to having to rely only on computational produced solutions. The structural design process in the POD model is currently based on manual manipulation of the design variables directly in the visual programming environment to generate different building variants. This process is not intuitive and can be time consuming when creating and evaluating a large number of options. The design space exploration in structural optimization studies can be automated [14]. Thus, in the next steps of the research, a multi-objective evolutionary optimization algorithm will be integrated into the POD model to automate the design search and to provide a wider spectrum of possible building solutions within a reduced amount of time for designers.

For real world implementation, the PLGO framework for ideal production layout planning should be evolved by enabling the algorithm to generate and place not only orthogonal cubes but produce L-shapes and irregular cubes in the layout. Furthermore, common objectives in facility layout planning such as material handling costs [65-67] and total completion time [68] are not yet implemented in the algorithm, calling for future research steps to receive much more realistic layout results. Currently, the PLGO framework generates 2-dimensional production layouts for single-story buildings and horizontal production processes. Prior research has examined multi-level layout allocation in the fields of structural layout design [74, 75] and architectural layouts [71], however, to enable vertical production, future research should focus on the evolvement of the method for multi-level production buildings.

The proof of concept was generated on two use cases (a hygiene production for the parametric production layout method and a food and hygiene production facility for the POD framework) and demonstrates, that the proposed method enables to identify potential savings in cost, resources and waste, to choose alternative building materials and search for different industrial building structures with maximum flexibility and decreased sustainability impact. It has to be stated that the main focus of this thesis was to demonstrate the proof of concept for the semi-automated integrated industrial building design and decision support method. Thereby, existing economic, recycling- and LCA-data and methodologies were used, however, their indicators and methods were not analyzed in depth, since the focus was on the development of the parametric design process and decision support method. The assessment of data quality, uncertainties associated with LCC and LCA methodologies, and strengths and weaknesses of the indicator databases used were not the focus of this dissertation. This could lead to divergent environmental and economic performance results within the proof of concepts conducted.

7 Future Outlook

This doctoral thesis is part of the larger research project BIMFlexi that aims to connect interdisciplinary teams of production planning and industrial building design at early design stage within a digital platform. The platform aims to couple digital planning methods (BIM and parametric modelling) with new technologies (hybrid-procedural optimization algorithms and multi-user VR) to enable design, analysis and optimization of flexible building structures with visualization and decision support. The results of this dissertation are essential components and important prerequisites for future research within BIMFlexi, as this doctoral thesis developed (1) a design guideline with parameters for flexible industrial buildings integrating production requirements, (2) flexibility metrics to assess industrial building and production planning systems, (3) a parametric production layout generation and optimization method for structural design integration, and (4) the holistic POD framework for integrated structural optimization with simultaneous multi-criteria performance assessment, as design and decision support method for flexible and sustainable industrial buildings. Ongoing research in BIMFlexi will increase the usability, collaboration, and visualization capabilities of the proposed parametric approach by establishing a mechanism to combine the POD framework with a multi-user VR platform. In virtual space, the design teams will be enabled to quickly explore 3D production and building structures and interactively inspect and alter the resulting designs to communicate designers' preferences. In addition, the structure and implemented data of the proposed method serve as basis for the development of a multi-objective evolutionary optimization algorithm that will be implemented in the POD model to automate the design search.

The presented POD framework acts as optimization and decision-making support method for building owners, architects and engineers to consider the synergies between production and building design and to optimize the flexibility and economic and environmental impacts such as costs, CO_2-emissions and waste of industrial building structures at early design stage. The POD framework can be useful in providing interdisciplinary stakeholders with a better understanding of the implications of their design decisions. On the one hand, the framework can be used by individual designers or engineers as an internal decision support and variant study tool, but on the other hand it can be applied in integrated design meetings to support interdisciplinary decision making.

As future outlook for the practical implementation of the POD framework the following fields can be identified:

- POD model for cost assessment in the tendering phase for construction firms
- Integration of the POD framework in BIM processes
- Adaption of the POD framework for office and residential buildings
- Application of the PLGO framework for real production layout planning
- Using the POD framework to generate training data for machine learning

The developed POD model, which enables automated structural analysis with parallel life cycle cost assessment, shows huge potential for **detailed cost assessments** and precise mass and quantity analyses of building structures and enclosure systems, which is relevant for construction firms in the tendering phase. An extension of the parametric framework as an optimization tool for the tendering phase is currently being tested within a proof of concept with a construction company from Austria based on a pilot project from the logistic sector.

The current design of the POD framework focuses primarily on the conceptual and early design stages of industrial buildings and the parametric modeling methodology is based on levels of abstraction. A future perspective is the coupling of the parametric design process with **BIM tools** to extend the design process to subsequent design stages. The coupling enables to transfer the optimized building structures, enclosure systems and production cubes to BIM models and lays the foundation for further post-processing and more detailed analysis.

The developed parametric method and recommendations regarding discipline-specific coupling, automated layout generation, and integration into structural design processes with simultaneous performance assessment are also useful for other construction projects such as **residential and office buildings**. The framework could be adapted to a method for automated space layout planning in connection with structural analysis of housing and office projects. This circumstance is particularly important for extended industrial building design studies, as this research has focused solely on the production and logistics hall of industrial facilities and neglected the associated office buildings.

As future outlook, the PLGO framework can be used by production planning offices as basis to improve and fasten their **real layout planning process**. The coupling and data exchange of the PLGO framework to an existing production planning tool (VisTable) has already been tested on a pilot project from a real hygiene production with an Austrian production planning office. The results of this pilot evaluation showed that the generated layout scenarios and their underlying quantitative evaluation results from the PLGO model can be bi-directly coupled, integrated and further modified in VisTable, which saves production planners a significant amount of time in finding of appropriate layout variants. The developed PLGO framework is not only of interest for production planners but can also be used by architects and structural engineers as it enables a fast, easy-to-use layout generation method that can be incorporated into building studies at an early design stage. A potential objective for future research is to use the POD framework to generate training data for a **machine learning pipeline** and incorporate prior human knowledge. The evolutionary algorithms of the PLGO model and POD model would be capable of generating a large number of production layout and building options in a short time, thus enables to collect training data by encoding the designer's feedback on generated outputs. The extension of the POD framework by including a machine learning model that learns from our data and integrates prior-human knowledge would predict structural building and production layouts that are closer to designer intentions and fasten the optimization process.

8 References

1. Heravi, G., M. Fathi, and S. Faeghi. *Evaluation of Sustainability Indicators of Industrial Buildings Focused on Petrochemical Projects*. Journal of Cleaner Production, 2015. 109: p. 92-107 DOI: 10.1016/j.jclepro.2015.06.133.
2. San-José Lombera, J.-T. and I. Garrucho Aprea. *A system approach to the environmental analysis of industrial buildings*. Building and Environment, 2010. 45(3): p. 673-683 DOI: https://doi.org/10.1016/j.buildenv.2009.08.012.
3. Oesterreich, T.D. and F. Teuteberg. *Understanding the implications of digitisation and automation in the context of Industry 4.0: A triangulation approach and elements of a research agenda for the construction industry*. Computers in Industry, 2016. 83: p. 121-139 DOI: https://doi.org/10.1016/j.compind.2016.09.006.
4. Flager, F. *The design of building structures for improved life-cycle performance*. Doctoral Thesis, 2003. Department of Civil and Environmental Engineering, Massachusetts Institute of Technology.
5. Gourlis, G. and I. Kovacic. *Building Information Modelling for analysis of energy efficient industrial buildings – A case study*. Renewable and Sustainable Energy Reviews, 2017. 68: p. 953-963 DOI: 10.1016/j.rser.2016.02.009.
6. Peukert, B., S. Benecke, J. Clavell, S. Neugebauer, N.F. Nissen, E. Uhlmann, K.-D. Lang, and M. Finkbeiner. *Addressing Sustainability and Flexibility in Manufacturing Via Smart Modular Machine Tool Frames to Support Sustainable Value Creation*. Procedia CIRP, 2015. 29: p. 514-519 DOI: https://doi.org/10.1016/j.procir.2015.02.181.
7. Cavalliere, C., G.R. Dell'Osso, F. Favia, and M. Lovicario. *BIM-based assessment metrics for the functional flexibility of building designs*. Automation in Construction, 2019. 107: p. 102925 DOI: https://doi.org/10.1016/j.autcon.2019.102925.
8. Madson, K.M., B. Franz, K.R. Molenaar, and G. Okudan Kremer. *Strategic development of flexible manufacturing facilities*. Engineering, Construction and Architectural Management, 2020. 27(6): p. 1299-1314 DOI: 10.1108/ECAM-03-2019-0139.
9. Ebade Esfahani, M., P. Burggräf, M. Dannapfel, D. Schneidermann, and N. Schwamborn. *Integrated factory modelling: Using BIM to disrupt the interface between manufacturing and construction in factory planning*. WIT Transactions on the Built Environment, 2019. 192: p. 143-155 DOI: 10.2495/BIM190131.
10. Bejjani, C., J. Utsch, T. Thiele, T. Meisen, S. Jeschke, and P. Burggräf. *Flow Chart Based Information Modeling for Factory Planning*. Procedia CIRP, 2018. 72: p. 410-415 DOI: https://doi.org/10.1016/j.procir.2018.03.259.
11. Kampker, A., A. Meckelnborg, P. Burggräf, and T. Netz. F*actory Planning Scrum: Integrative Factory Planning with Agile Project Management*. in Conference Proceedings of COMA´ 13. 2013. Stellenbosch, South Africa.
12. Mueller, C.T. *Computational exploration of the structural design space*. Doctoral Thesis, 2014. Department of Architecture, Massachusetts Institute of Technology.
13. Mueller, C.T. and J.A. Ochsendorf. *Combining structural performance and designer preferences in evolutionary design space exploration*. Automation in Construction, 2015. 52: p. 70-82 DOI: https://doi.org/10.1016/j.autcon.2015.02.011.

14. Brown, N.C., V. Jusiega, and C.T. Mueller. I*mplementing data-driven parametric building design with a flexible toolbox*. Automation in Construction, 2020. 118: p. 103252 DOI: https://doi.org/10.1016/j.autcon.2020.103252.

15. Haymaker, J., M. Bernal, M.T. Marshall, V. Okhoya, A. Szilasi, R. Rezaee, C. Chen, A. Salveson, J. Brechtel, L. Deckinga, H. Hasan, P. Ewing, and B. Welle. *Design space construction: A framework to support collaborative, parametric decision making*. Journal of Information Technology in Construction (ITcon), 2018. 23: p. 157-178 DOI: http://www.itcon.org/2018/8.

16. Lenz, L., M. Höpfner, P. Spyridis, K.C. Weist, and M. Gralla. *BIM Approach for Automatic Decision Support: Case Study Fastening Systems in Factory Adaptation Planning*. in Proceedings of the 2019 European Conference on Computing in Construction, 2019. DOI: 10.35490/EC3.2019.136.

17. Ebade Esfahani, M., P. Burggräf, M. Dannapfel, and N. Schwamborn. *How to Improve Collaboration Efficiency in the Built Environment of Factories by Using an Integrated Factory Modelling Concept – An Expert Study*. International Journal of Design & Nature and Ecodynamics, 2020. 15: p. 473-481 DOI: 10.18280/ijdne.150403.

18. Büscher, C., T. Meisen, D. Schilberg, and S. Jeschke. *VPI-FP: an integrative information system for factory planning*. International Journal of Production Research, 2016. 54(8): p. 2215-2226 DOI: 10.1080/00207543.2015.1057298.

19. Weerasinghe, A.S., T. Ramachandra, and J.O.B. Rotimi. *Comparative life-cycle cost (LCC) study of green and traditional industrial buildings in Sri Lanka*. Energy and Buildings, 2021. 234: p. 110732 DOI: https://doi.org/10.1016/j.enbuild.2021.110732.

20. Li, S., Y. Lu, H.W. Kua, and R. Chang. T*he economics of green buildings: A life cycle cost analysis of non-residential buildings in tropic climates*. Journal of Cleaner Production, 2020. 252: p. 119771 DOI: https://doi.org/10.1016/j.jclepro.2019.119771.

21. Opher, T., M. Duhamel, I.D. Posen, D.K. Panesar, R. Brugmann, A. Roy, R. Zizzo, L. Sequeira, A. Anvari, and H.L. MacLean. L*ife cycle GHG assessment of a building restoration: Case study of a heritage industrial building in Toronto, Canada*. Journal of Cleaner Production, 2021. 279: p. 123819 DOI: https://doi.org/10.1016/j.jclepro.2020.123819.

22. Tulevech, S.M., D.J. Hage, S.K. Jorgensen, C.L. Guensler, R. Himmler, and S.H. Gheewala. *Life cycle assessment: a multi-scenario case study of a low-energy industrial building in Thailand*. Energy and Buildings, 2018. 168: p. 191-200 DOI: https://doi.org/10.1016/j.enbuild.2018.03.011.

23. Živković, M. and G. Jovanović. *A method for evaluating the degree of housing unit flexibility in multi-family housing*. Architecture and Civil Engineering 10, 2012: p. 17-32 DOI: 10.2298/FUACE1201017Z.

24. Jain, A., P.K. Jain, F.T.S. Chan, and S. Singh. *A review on manufacturing flexibility*. International Journal of Production Research, 2013. 51(19): p. 5946-5970 DOI: 10.1080/00207543.2013.824627.

25. Long, F., P. Zeiler, and B. Bertsche. *Modelling the flexibility of production systems in Industry 4.0 for analysing their productivity and availability with high-level Petri nets*. IFAC-PapersOnLine, 2017. 50(1): p. 5680-5687 DOI: https://doi.org/10.1016/j.ifacol.2017.08.1118.

26. Reisinger, J., I. Kovacic, H. Kaufmann, P. Kan, and I. Podkosova. *Framework Proposal for a BIM-Based Digital Platform for Flexible Design and Optimization of*

Industrial Buildings for Industry 4.0. in ICCCBE/W78 Virtual Joint Conference. 2020: Sao Paulo, Brazil. p. 401-415 DOI: 10.46421/2706-6568.37.2020.paper029.

27. De Paris, S.R. and C.N.L. Lopes. *Housing flexibility problem: Review of recent limitations and solutions*. Frontiers of Architectural Research, 2018. 7(1): p. 80-91 DOI: https://doi.org/10.1016/j.foar.2017.11.004.
28. Sethi, A.K. and S.P. Sethi. *Flexibility in manufacturing: A survey*. International Journal of Flexible Manufacturing Systems, 1990. 2(4): p. 289-328 DOI: 10.1007/BF00186471.
29. Gosling, J., M. Naim, P. Sassi, L. Iosif, and R. Lark. *Flexible buildings for an adaptable and sustainable future*. in Association of Researchers in Construction Management. 2008. Cardiff, UK.
30. Cardin, M.-A., M. Ranjbar-Bourani, and R. de Neufville. *Improving the Lifecycle Performance of Engineering Projects with Flexible Strategies: Example of On-Shore LNG Production Design*. Systems Engineering, 2015. 18 DOI: 10.1002/sys.21301.
31. Slaughter, E.S. *Design strategies to increase building flexibility*. Building Research & Information, 2001. 29(3): p. 208-217 DOI: 10.1080/09613210010027693.
32. Wiendahl, H.P., H.A. ElMaraghy, P. Nyhuis, M.F. Zäh, H.H. Wiendahl, N. Duffie, and M. Brieke. *Changeable Manufacturing - Classification, Design and Operation*. CIRP Annals, 2007. 56(2): p. 783-809 DOI: https://doi.org/10.1016/j.cirp.2007.10.003.
33. Cellucci, C. and M. Sivo. *The Flexible Housing: Criteria and Strategies for Implementation of the Flexibility*. Journal of Civil Engineering and Architecture, 2015. 9: p. 845-852 DOI: 10.17265/1934-7359/2015.07.011.
34. Till, J. and T. Schneider. *Flexible housing: the means to the end*. Architectural Research Quarterly, 2006. 9(3-4): p. 287-296 DOI: 10.1017/S1359135505000345.
35. Beach, R., A.P. Muhlemann, D.H.R. Price, A. Paterson, and J.A. Sharp. *A review of manufacturing flexibility*. European Journal of Operational Research, 2000. 122(1): p. 41-57 DOI: https://doi.org/10.1016/S0377-2217(99)00062-4.
36. Cousens, A., M. Szwejczewski, and M. Sweeney. *A process for managing manufacturing flexibility*. INT J OPER PROD MANAGE, 2009. 29: p. 357-385 DOI: 10.1108/01443570910945828.
37. Browne, J., D. Dubois, K. Rathmill, S. Sethi, and K. Stecke. *Classification of Flexible Manufacturing Systems*. The FMS Magazine, 1984. 2.
38. Geraedts, R. FLEX 4.0, *A Practical Instrument to Assess the Adaptive Capacity of Buildings*. Energy Procedia, 2016. 96: p. 568-579 DOI: https://doi.org/10.1016/j.egypro.2016.09.102.
39. Lieder, M. and A. Rashid. *Towards circular economy implementation: a comprehensive review in context of manufacturing industry*. Journal of Cleaner Production, 2016. 115: p. 36-51 DOI: https://doi.org/10.1016/j.jclepro.2015.12.042.
40. Rodrigues, V., A.A. Martins, M.I. Nunes, A. Quintas, T.M. Mata, and N.S. Caetano. *LCA of constructing an industrial building: focus on embodied carbon and energy*. Energy Procedia, 2018. 153: p. 420-425 DOI: https://doi.org/10.1016/j.egypro.2018.10.018.

41. ISO 14040:2006 Environmental management — Life cycle assessment — Principles and framework. 2006, European Committee for Standardization.

42. SimaPro Software. [accessed 14.02.2022]; Available from: https://simapro.com/.

43. Legep GmbH. 2022 [accessed 14.02.2022]; Available from: https://legep.de/produkte/legep-okobilanz/.

44. GaBi Software, Sphera Solutions Inc. 2022 [accessed 14.02.2022]; Available from: https://gabi.sphera.com/deutsch/index/.

45. OneClickLCA Ltd. 2021 [accessed 14.02.2022]; Available from: https://www.oneclicklca.com/.

46. Building Transparency, Tally Software. 2021 [accessed 14.02.2022]; Available from: https://choosetally.com/.

47. Eco2soft, Baubook GmbH. 2022 [accessed 14.02.2022]; Available from: https://www.baubook.at/eco2soft/.

48. Baubook GmbH - Die Datenbank für ökologisches Bauen & Sanieren. 2022 [accessed 14.02.2022]; Available from: http://www.baubook.info/.

49. IBO. *OI3-Berechnungsleitfaden Version 4.0*. 2018, IBO – Österreichisches Institut für Bauen und Ökologie GmbH: Vienna. p. 21.

50. Honic, M., I. Kovacic, and H. Rechberger. *Improving the recycling potential of buildings through Material Passports (MP): An Austrian case study*. Journal of Cleaner Production, 2019. 217: p. 787-797 DOI: https://doi.org/10.1016/j.jclepro.2019.01.212.

51. Blengini, G.A. *Life cycle of buildings, demolition and recycling potential: A case study in Turin, Italy*. Building and Environment, 2009. 44(2): p. 319-330 DOI: https://doi.org/10.1016/j.buildenv.2008.03.007.

52. Thormark, C. *The effect of material choice on the total energy need and recycling potential of a building*. Building and Environment, 2006. 41(8): p. 1019-1026 DOI: https://doi.org/10.1016/j.buildenv.2005.04.026.

53. Honic, M., I. Kovacic, and H. Rechberger. *Concept for a BIM-based Material Passport for buildings*. IOP Conference Series: Earth and Environmental Science, 2019. 225: p. 012073 DOI: 10.1088/1755-1315/225/1/012073.

54. IBO. *Leitfaden zur Berechnung des Entsorgungsindikators EI Kon von Bauteilen und des Entsorgungsindikators EI10 auf Gebäudeebene*. 2018, IBO - Österreichisches Institut für Bauen und Ökologie GmbH. p. 14.

55. ISO/TC59, Building construction. *ISO 15686-5 - Buildings and constructed assets - service life planning - part5: life-cycle costing*. 2017. ISO International Organization for Standardization. p. 43.

56. OneClickLCA Ltd. Life-Cycle-Costing-Software. 2021 [accessed 14.02.2022]; Available from: https://www.oneclicklca.com/construction/life-cycle-costing-software/.

57. Kovacic, I. and V. Zoller. *Building life cycle optimization tools for early design phases*. Energy, 2015. 92: p. 409-419 DOI: 10.1016/j.energy.2015.03.027.

58. DGNB GmbH. *DGNB System – Kriterienkatalog Gebäude Neubau - ENV1.1 Ökobilanz des Gebäudes*. 2018. p. 58. Available from: https://static.dgnb.de/fileadmin/dgnb-system/de/gebaeude/neubau/kriterien/02_ENV1.1_Oekobilanz-des-Gebaeudes.pdf

59. Bundesministerium des Innern, für Bau und Heimat (BMI). *Bewertungssystem Nachhaltiges Bauen (BNB)*. 2020 [accessed 14.02.2022]; Available from: https://www.bnb-nachhaltigesbauen.de/.

60. ib-data GmbH. *ABK LEKOS Lebenszykluskostenberechnung*. 2020 [accessed 14.2.2022]; Available from: https://www.abk.at/produkte/projektmanagement/kostenmanagement/#c7689.

61. Vierschilling, S.P., M. Dannapfel, S. Losse, and O. Matzke. *Generative Design In Factory Layout Planning: An Application Of Evolutionary Computing Within The Creation Of Production Logistic Concepts*. In: Proceedings of the 1st Conference on Production Systems and Logistics, 2020. South Africa, DOI: 10.15488/9656.

62. Garcia-Hernandez, L., J.A. Garcia-Hernandez, L. Salas-Morera, C. Carmona-Muñoz, N.S. Alghamdi, J.V. de Oliveira, and S. Salcedo-Sanz. *Addressing Unequal Area Facility Layout Problems with the Coral Reef Optimization algorithm with Substrate Layers*. Engineering Applications of Artificial Intelligence, 2020. 93: p. 103697 DOI: https://doi.org/10.1016/j.engappai.2020.103697.

63. La Scalia, G., R. Micale, and M. Enea. *Facility layout problem: Bibliometric and benchmarking analysis*. International Journal of Industrial Engineering Computations, 2019: p. 453-472 DOI: 10.5267/j.ijiec.2019.5.001.

64. Aiello, G., G. La Scalia, and M. Enea. *A non dominated ranking Multi Objective Genetic Algorithm and electre method for unequal area facility layout problems*. Expert Systems with Applications, 2013. 40(12): p. 4812-4819 DOI: https://doi.org/10.1016/j.eswa.2013.02.026.

65. Shabaka, A.I. and H.A. ElMaraghy. *A model for generating optimal process plans in RMS*. International Journal of Computer Integrated Manufacturing, 2008. 21(2): p. 180-194 DOI: 10.1080/09511920701607741.

66. Palomo-Romero, J.M., L. Salas-Morera, and L. García-Hernández. *An island model genetic algorithm for unequal area facility layout problems*. Expert Systems with Applications, 2017. 68: p. 151-162 DOI: https://doi.org/10.1016/j.eswa.2016.10.004.

67. Chae, J. and A.C. Regan. *Layout design problems with heterogeneous area constraints*. Comput. Ind. Eng., 2016. 102(C): p. 198–207 DOI: 10.1016/j.cie.2016.10.016.

68. Touzout, F.A. and L. Benyoucef. *Multi-objective sustainable process plan generation in a reconfigurable manufacturing environment: exact and adapted evolutionary approaches*. International Journal of Production Research, 2019. 57(8): p. 2531-2547 DOI: 10.1080/00207543.2018.1522006.

69. Pérez-Gosende, P., J. Mula, and M. Díaz-Madroñero. *Overview of Dynamic Facility Layout Planning as a Sustainability Strategy*. Sustainability, 2020. 12(19): p. 8277.

70. Upasani, N., K. Shekhawat, and G. Sachdeva. *Automated generation of dimensioned rectangular floorplans*. Automation in Construction, 2020. 113: p. 103149 DOI: https://doi.org/10.1016/j.autcon.2020.103149.

71. Rodrigues, E., A.R. Gaspar, and Á. Gomes. *An approach to the multi-level space allocation problem in architecture using a hybrid evolutionary technique*. Automation in Construction, 2013. 35: p. 482-498 DOI: https://doi.org/10.1016/j.autcon.2013.06.005.

72. Dino, I.G. *An evolutionary approach for 3D architectural space layout design exploration*. Automation in Construction, 2016. 69: p. 131-150 DOI: https://doi.org/10.1016/j.autcon.2016.05.020.

73. Nourian, P., S. Rezvani, and S. Sariyildiz. *Designing with Space Syntax A configurative approach to architectural layout, proposing a computational methodology*. In: Proceedings of 31st eCAADe Conference, 2013. Delft Netherlands.

74. Claessens, D.P.H., S. Boonstra, and H. Hofmeyer. *Spatial zoning for better structural topology design and performance*. Advanced Engineering Informatics, 2020. 46: p. 101162 DOI: https://doi.org/10.1016/j.aei.2020.101162.

75. Boonstra, S., K. van der Blom, H. Hofmeyer, and M.T.M. Emmerich. *Conceptual structural system layouts via design response grammars and evolutionary algorithms*. Automation in Construction, 2020. 116: p. 103009 DOI: https://doi.org/10.1016/j.autcon.2019.103009.

76. Kovacic, I., L. Waltenberger, and G. Gourlis. *Tool for life cycle analysis of facade-systems for industrial buildings*. Journal of Cleaner Production, 2016. 130: p. 260-272 DOI: https://doi.org/10.1016/j.jclepro.2015.10.063.

77. Röck, M., A. Hollberg, G. Habert, and A. Passer. *LCA and BIM: Visualization of environmental potentials in building construction at early design stages*. Building and Environment, 2018. 140: p. 153-161 DOI: https://doi.org/10.1016/j.buildenv.2018.05.006.

78. Danhaive, R. and C. Mueller. *Combining parametric modeling and interactive optimization for high-performance and creative structural design*. In: Conference Proceedings of International Association for Shell and Spatial Structures (IASS) Symposium 2015 At Amsterdam, 2015.

79. Kamalakkannan, S. and A.K. Kulatunga. *Optimization of eco-design decisions using a parametric life cycle assessment*. Sustainable Production and Consumption, 2021. 27: p. 1297-1316 DOI: https://doi.org/10.1016/j.spc.2021.03.006.

80. Hollberg, A. and J. Ruth. *LCA in architectural design—a parametric approach*. The International Journal of Life Cycle Assessment, 2016. 21 DOI: 10.1007/s11367-016-1065-1.

81. Robert McNeel & Associates. Grasshopper. 2020 [accessed 29.01.2020]; Available from: https://www.rhino3d.com/6/new/grasshopper.

82. Preisinger, C. and M. Heimrath. *Karamba—A Toolkit for Parametric Structural Design*. Structural Engineering International, 2014. 24(2): p. 217-221 DOI: 10.2749/101686614X13830790993483.

83. Brown, N.C. and C.T. Mueller. *Design for structural and energy performance of long span buildings using geometric multi-objective optimization*. Energy and Buildings, 2016. 127: p. 748-761 DOI: https://doi.org/10.1016/j.enbuild.2016.05.090.

84. Pan, W., M. Turrin, C. Louter, S. Sariyildiz, and Y. Sun. *Integrating multi-functional space and long-span structure in the early design stage of indoor sports arenas by using parametric modelling and multi-objective optimization*. Journal of Building Engineering, 2019. 22: p. 464-485 DOI: https://doi.org/10.1016/j.jobe.2019.01.006.

85. Robert McNeel & Associates. Rhinoceros 3D. [accessed 29.01.2020]; Available from: https://www.rhino3d.com/.

86. Apellániz, D., P. Pasanen, and C. Gengnagel. *A Holistic and Parametric Approach for Life Cycle Assessment in the Early Design Stages*. In: Proceedings of 12th annual Symposium on Simulation for Architecture and Urban Design (SimAUD), 2021.

87. Moethu, food4Rhino. Tortuga - LCA in Grasshopper. [accessed 14.02.2022]; Available from: https://www.food4rhino.com/en/app/tortuga-lca-grasshopper.

88. CAALA GmbH. CAALA Software. 2022 [accessed 14.02.2022]; Available from: https://caala.de/.

89. Basic, S., A. Hollberg, A. Galimshina, and G. Habert. *A design integrated parametric tool for real-time Life Cycle Assessment - Bombyx project*. in IOP Conference Series: Earth and Environmental Science. 2019. DOI: 10.1088/1755-1315/323/1/012112.

90. Büscher, C., H. Voet, T. Meisen, M. Krunke, K. Kreisköther, A. Kampker, D. Schilberg, and S. Jeschke. *Improving Factory Planning by Analyzing Process Dependencies*. Procedia CIRP, 2014. 17: p. 38-43 DOI: 10.1016/j.procir.2014.01.142.

91. Büscher, C., H. Voet, M. Krunke, P. Burggräf, T. Meisen, and S. Jeschke. *Semantic Information Modelling for Factory Planning Projects*. Procedia CIRP, 2016. 41: p. 478-483 DOI: https://doi.org/10.1016/j.procir.2015.12.022.

92. Dombrowski, U.H., S;Laviola, C; Rustom, S; . *Planungsleitfaden Zukunft Industriebau - Ganzheitliche Integration und Optimierung des Planungs- und Realisierungsprozesses für zukunftsweisende und nachhaltige Industriegebäude*. 2011: Fraunhofer IRB Verlag.

93. Graefenstein, J., J. Winkels, L. Lenz, K.C. Weist, K. Krebil, and M. Gralla. *A Hybrid Approach of Modular Planning – Synchronizing Factory and Building Planning by Using Component based Synthesis*. In: Proceedings of International Conference on System Sciences, Hawai, 2020. DOI: 10.24251/HICSS.2020.806.

94. Delbrügger, T., L. Lenz, D. Losch, and J. Rosmann. *A navigation framework for digital twins of factories based on building information modeling*. In Proceedings of 22nd IEEE International Conference on Emerging Technologies and Factory Automation (ETFA). 2017. p. 1-4 DOI: 10.1109/ETFA.2017.8247712.

95. Smolek, P., I. Leobner, B. Heinzl, G. Gourlis, and K. Ponweiser. *A Method for Real-Time Aggregation of a Product Footprint during Manufacturing*. Journal of Sustainable Development of Energy, Water and Environment Systems, 2016. 4: p. 360-378 DOI: http://dx.doi.org/10.13044/j.sdewes.2016.04.0028.

96. Yin, R.K. *Case study research : design and methods*. Los Angeles, California , Sage Publ, 2009. 4th edition, 219 pages.

97. BKI-Baukosteninformationszentrum. *BKI Baukosten Gebäude, Positionen und Bauelemente Neubau 2020 - Teil 1-3: Statistische Kostenkennwerte*. Vol. 1. 2020, Stuttgart: Müller Rudolf. 2515.

98. Preisinger, C. Karamba3D. [accessed 29.01.2020]; Available from: https://www.karamba3d.com/.

99. DGNB GmbH. *DGNB System – Kriterienkatalog Gebäude Neubau*. Vol. Version 2018. Stuttgart, Deutschlang. 57. Accessible: https://static.dgnb.de/fileadmin/dgnb-system/de/gebaeude/neubau/kriterien/02_ENV1.1_Oekobilanz-des-Gebaeudes.pdf

Section II

Scientific peer-reviewed papers

P1

Julia Reisinger, Patrick Hollinsky and Iva Kovacic

"Design Guideline for Flexible Industrial Buildings Integrating Industry 4.0 Parameters."

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Article

Design Guideline for Flexible Industrial Buildings Integrating Industry 4.0 Parameters

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Abstract: The emergence of Industry 4.0 can contribute to sustainable development, but most concepts have not yet received much attention in industrial building design. Industry 4.0 aims to realize production in batch size of one and product individualization on demand. Constant reconfiguration and expansion of production systems demand highly flexible building structures to prolong service life and reduce economic and environmental impacts. However, most research and tools focus on either production system or building optimization. There is a lack of holistic approaches that combine these two aspects. This paper presents a systematic design guideline for flexible industrial buildings towards the requirements of Industry 4.0, integrating building and production planning. The methodology employs literature research and a multiple case study based on expert interviews. The design guideline is presented in the form of a categorized parameter catalogue that classifies the results, on the one hand, into the levels of (O) objectives, (T) technical parameters and (P) planning process, and on the other hand, into (S) success factors, (I) suggestions for improvement and (D) deficits. The findings identify flexibility, structural design parameters and an integrated computational design approach at early design stage as potential success factors for integrated industrial building design (IIBD). The results set the basis to develop a multi-objective optimization and decision-making support tool for IIBD in future research.

Keywords: integrated industrial building design; Industry 4.0; sustainable building design; flexible production facilities; integrated design; design guidance

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1. Introduction

Industry 4.0 has received much attention in recent years and describes the trend towards increased digitization and automation of the manufacturing environment [1]. The concept mainly includes enabling technologies such as cyber-physical systems (CPS), Internet of Things (IoT) and cloud computing [2], resulting in a paradigm shift in industrial production [3]. While originally applied to manufacturing systems, the digital transformation of the fourth industrial revolution is also changing the construction sector [4]. However, usually, this concept mainly focuses on the dimensions of production and economic profits. This limited perspective creates multiple problems for other dimensions and often neglects sustainability aspects [5].

The construction industry is crucial for sustainable development as buildings account for 30% to 40% of the primary energy use worldwide [6] and consume up to 40% of all raw materials [7]. In particular, industrial buildings, here defined as facilities in which products are manufactured, play a key role in sustainable development as they produce and consume a significant amount of material, energy and waste in the construction and operation phases [8]. The emergence of Industry 4.0 can contribute to achieving the Sustainable Development Goals (SDGs) [9] by evolving digital sustainable operations [10], yet most of the concepts have not gained much attention in the construction industry [1]. The essence of Industry 4.0 is inter- and transdisciplinary integration of existing and new technologies [2]. Due to upcoming sustainability requirements, a more integrated practice in building design and a focus on early design stages is needed. This holistic approach enables and promotes the collaboration of multiple disciplines and offers real-time decision-making supports [11]. A high fragmentation of building design processes hinders the communication and management of complex design decisions. It is also challenging for scattered stakeholders to assess the impact of decisions on the project performance [12]. Moreover, interfaces and data exchange between the domain-disciplines in factory design have been little researched [13], making the integration of production system planning and building design challenging [14]. Consequently, in order to enhance sustainability, the focus should be on integrated industrial building design (IIBD), incorporating building and production planning methods already at the early design stage.

Prior research has shown that flexibility can improve the sustainability of manufacturing processes [15] and building designs [16,17]. Industry 4.0 aims to realize production in batch size of one and individualization on demand within short development periods [3]. Constant reconfiguration and expansion of production systems demand highly flexible building systems to prolong the factories service life, thereby decreasing the economic and environmental impact [18]. Yet there is a lack of formal design guidance supporting flexibility within architectural and engineering systems used for production facilities [19]. Usually, the building is planned around the product and process requirements not incorporating the capability to respond quickly enough to changes [20]. Thus, to improve the design outcome and reduce the environmental impact of industrial buildings, the building systems (envelope, load-bearing structure, building service equipment) should be designed towards increased flexibility to enable reconfiguration of manufacturing systems.

The load-bearing structure, as the most rigid element with the longest service life in a building [21] is a key determinant of the adaptability and transformability of manufacturing systems. Flexible load-bearing structures, which can be implemented by means of wide-span ceiling or girder systems, sufficiently high stories and different load carrying capacities, can prolong the building's service life [22]. Maximizing the flexibility of building structures can minimize costs and time required for rescheduling and the identification of interdependencies to other discipline-specific systems is challenging [23]. Currently available structural analysis tools are not sufficient for the early design stage as they tend to focus on precision rather than flexibility. They also lack interoperability with other design tools [24]. Furthermore, most structural analysis methods provide feedback only to the structural engineer and do not support an integrated performance improvement [25]. Digital industrial building models that do not properly address the interaction between production and building design disciplines may later lead to inflexible solutions. The same lack of flexibility may result if structural considerations are subservient to architectural and production goals. Thus, a precondition for the realization of flexible industrial buildings for Industry 4.0 is the optimization of the load-bearing structure early in the design process and the integration of a high number of interrelated discipline-specific design parameters.

An IIBD approach requires the utilization of powerful digital tools, which allow holistic simulation, prediction and optimization to support close collaboration of all stakeholders. The digital transformation of the construction industry can be seen as a new opportunity to overcome the lack in productivity by pushing the collaboration in an interdisciplinary data-driven environment [26]. However, the models, data and processes of the disciplines involved in planning and operating of factories lack interoperability and are kept in discipline-specific silo thinking [27]. Regarding optimization and decision-support tools in factory planning, prior research has mostly been focusing on optimization on product- or manufacturing process level [28,29], energy efficiency in production [30,31] or sustainable manufacturing [32,33] and paid less attention to the integration of building structure or -services information [8]. Several authors proposed models concentrating on the industrial building, evaluating the environmental performance of building elements through life-cycle assessment [34–36] or optimizing the buildings' energy performance [37,38]. Holistic digital models that optimize industrial building structures towards maximum flexibility, thus sustainability, receive little attention and fail to fully incorporate both production and building design.

Hence, to enable the realization of sustainable industrial buildings, load-bearing structures of maximum flexibility are required for rapid reconfigurability and adaptability of production systems. A prerequisite for IIBD is the integrated collaboration of all stakeholders from the early design stage and the development of powerful digital tools with efficient user interfaces that incorporate building and production planning knowledge. In this context, this paper addresses the lack of formal guidelines that support the design of flexible industrial buildings for the requirements of Industry 4.0 and integrate the parameters of production and building design. The main research questions addressed in this paper are: what are the critical parameters for a holistic design approach that combines building and production planning and how to generate methods, models and processes for flexible and sustainable production facilities? To answer the research questions, the following hypotheses are investigated in this paper:

Hypothesis 1 (H1). *The primary objective for the realization of sustainable industrial buildings is to maximize the flexibility in order to accommodate the fast-moving processes of Industry 4.0.*

Hypothesis 2 (H2). *The optimization of the load-bearing structure at the early design stage is crucial for enhancing the flexibility of industrial buildings.*

Hypothesis 3 (H3). *The optimization towards maximum flexibility is characterized by a high degree of complexity and interdependencies of interdisciplinary parameters and therefore requires an integrated planning approach supported by powerful computational tools.*

This paper presents ongoing research conducted within the funded research project BIMFlexi, which aims to develop a digital platform for design and optimization of flexible industrial buildings towards the needs of Industry 4.0 by integrating production and building planning. The goal of the presented research is to develop a systematic design guideline for sustainable industrial building design for Industry 4.0 that integrates building and production planning knowledge in form of a categorized parameter catalogue. The research employs the methods of literature research and expert interviews within a multiple case study to identify (O) objectives, (T) technical parameters and (P) demands on the planning process in IIBD. By analyzing the core content of the expert statements gathered from the interviews, the parameters are further classified into (S) success factors, (I) suggestions for improvement and (D) deficits. The results of this paper serve as basis for the development of a holistic simulation, optimization and decision-making support tool for flexible IIBD, which will be addressed in the next steps of our research.

This paper is structured as follows: in the next section, the state of the art and research on Industry 4.0, flexibility and design parameters, data and model integration and decision-making support in IIBD is examined through literature review. Second, the methodology is described, where a multiple case study of five real industrial building projects with 15 conducted expert interviews is presented, followed by the analysis of the questionnaire results. Based on the analysis results, the developed design guideline in form of a categorized parameter catalogue is presented. In the concluding section, future steps and challenges are discussed.

2. Literature Review

The main purpose of this research is to create a design guideline for the realization of flexible industrial buildings considering Industry 4.0 needs. The study aims to increase the sustainability of production facilities through integration of building design and production planning.

2.1. Industry 4.0 and Sustainable Industrial Building Design

Sustainability at an economic, ecological and social level is an increasingly important goal in factory planning processes [39]. Industry 4.0 technologies can enable the achievement of sustainability by acting as a novel driver of traditional supply chains through digitization with the aim of resource efficiency and circularity. The development of new concepts for sustainable Industry 4.0 can lead to a greater efficiency of functions or actions by using IT-based technologies and tools for industry-specific data exchange and storage, to manage big data, to increase transparency and to improve resource efficiency [10]. Nevertheless, as Industry 4.0 concepts deploy scenarios of digitization, integration and automation, they require more materials, energy and disposal as the infrastructure needs new highly demanding machines, software, and hardware [5]. Apart from the energy and material used by manufacturing processes, industrial buildings consume considerable amounts of energy, materials and waste for construction and operation. Oesterreich and Teuteberg [1] point to benefits the construction industry could obtain through Industry 4.0, but the resource and energy optimization of industrial buildings have been regarded as secondary issues compared to the management of the production processes and workforce [34,38]. Industrial building and production systems are generally heavy, fixed, and normally irreversible once construction has been completed [40]. The service life of a building is highly dependent on the durability of the physical structure, whereas the longest lasting building component is the load-bearing structure. The load-bearing structure has a service life of approximately 30 to 300 years; in comparison to the exterior building enclosure which changes every 20 years and the building service equipment which has a lifetime of 7 to 15 years [21]. The economic life cycle of industrial buildings is characterized by very short life cycles ranging from 15 to 30 years, compared to classical buildings that range from 50 to 80 years. The prolongation of industrial buildings service life could increase economic and environmental performance but demands that the building structure accommodates flexible and expandable production layouts [18]. Geraedts [41] establishes a direct link between the flexibility of a building and its sustainability. By extending the buildings service life, the energy and emissions required to construct and operate the building can be better distributed over the years of use. Thus, the focus in flexible industrial building design needs to be on a coherent planning and respecting objectives and parameters of both the rigid building and flexible production systems.

2.2. Flexibililty and Design Parameters in IIBD

It is widely acknowledged in the research and industry communities that flexible, adaptable and expandable buildings increase sustainability. Incorporating flexibility early in the design process can reduce lifetime investments in production facilities which are subject to change [42]. The flexibility of a building can be defined as its capacity to adapt to changes in use [43], while a flexible production enables the response to customer orders quickly, provides a broad product range, or introduces new products to the range effortlessly [44]. Various research defined concepts and metrics for flexibility in residential building design [17,45–47] or the adaptive re-use of office and industrial buildings [48]. Slaughter [23] presents three general types of expected building changes: 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. Further factors influencing the buildings flexibility are the material standards, production, planning for future changes and service life, installations, financial aspects and the aspects of awareness on building flexibility [49]. Cavalliere, et al. [17] define metrics of housing flexibility such as structural modularity, geometrical regularity of plan, location of technical service, removable building elements, percentage/orientation of windows and internal mobile partitions. Geraedts [41] identifies flexibility key performance indicators and divides them in the layers of site, structure, skin, facilities and space. The indicators for structural flexibility include 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, while the building service equipment respect the surplus capacity of facilities, distribution facilities, location sources facilities along with others. Madson, et al. [19] highlighted the lack of formal design guidance, supporting flexibility within architectural and engineering systems of production facilities and describe design features for flexible manufacturing facilities such as additional floor space, fixed utility routing, additional floor-to-ceiling height, pre-investment in foundation, large column bays, modular production area and others. On the manufacturing side, Browne et al. [50] and Sethi and Sethi [51] defined the eleven most common production flexibility dimensions as: machine flexibility, operation flexibility, routing flexibility, volume flexibility, expansion flexibility, process flexibility, product flexibility, production flexibility, material handling flexibility, programme flexibility and market flexibility but neglected the factor building. Wiendahl et al. [52] introduces the term changeable manufacturing as characteristic to accomplish foresighted adjustments of the production facility structures and processes on all levels, including the factor building and describe the five transformation enablers as universality, scalability, modularity, mobility and compatibility. Other research considered the flexible design of a specific facility type such as food processing facilities [53] and pharmaceutical facilities [54]. However, the term flexibility in production is not uniform and faces three issues: (1) measuring flexibility is not easy; (2) the produced products of a plant do not always reflect its flexibility and (3) it is often unclear which general features of a plant must be changed in order to make its operations flexible [44]. A rising number of research has investigated concepts and criteria of flexibility in both building and production planning. However, flexibility in production facilities is not a one-size-fits-all approach; rather it can be cultivated at varying levels by a series of design choices [19]. The stakeholder needs decision rules to guide the use of flexibility as the choice of design decisions affect the lifecycle performance of the system, benefitting from guidance and thorough evaluation [55]. Therefore, the definition of joint design parameters for IIBD is the focus of this paper in order to provide design guidance towards flexible industrial buildings by integrating Industry 4.0 needs to support in optimization and decision-making at early project stages.

In addition to flexibility, previous research on industrial building design and construction has focused on sustainability performance, typical design criteria, processes and models. Shen, et al. [56] described the major factors affecting sustainability performance across a construction projects lifecycle and suggest considering life-cycle costs, project layout, material choice, knowledge of designers, effective communication among stakeholders and modular/standardized design to reduce waste. Shen, et al. [57] defined key assessment factors to assess the sustainability performance of infrastructure projects as stating life-cycle costs, ecological effects, effect on land, air and water, waste generation and energy savings. Rodrigues, et al. [35] stated that building materials especially the ones from load-bearing structure and enclosure systems are the main responsible for the total embodied energy and carbon in industrial buildings. As the element with the longest service life, the structural system has a vast impact on the life-cycle performance of production systems [58,59]. Nadoushani and Akbarnezhad [60] described the lateral load resisting system, material of the structure and the height of the structure as important parameter in structural hall design. San-José Lombera and Garrucho Aprea [58] presented an integrated value model for sustainable assessment of industrial buildings, defining sustainability criteria under the study cope of functionality, economy, environment, social, safety and aesthetics. Lee, et al. [61] developed a factorial design space exploration approach to support in multi-criteria design decision-making (MCDM), investigating the energy performance, environmental impact and cost effectiveness across the life-cycle, identifying the design parameter for interest are insulation values, construction types, skylight coverage and transpired solar collector coverage. Vardopoulos [62] investigated critical sustainable development factors of industrial buildings for adaptive reuse such as energy efficiency, extending the life cycle of buildings and materials, reduce greenhouse gases, reduce resource consumption and prevent urban sprawl. The above-mentioned research is remarkable but neglects the impact of changing production systems. Wiendahl, et al. [63] present parameters and dependencies of production and building design in factories, describing primary building design criteria as demountable façade systems, enclosure system type, primary and secondary load-bearing structure type, axis grid, dimensioning and position of foundations and sprinkler systems for fire safety. A variety of research is investigating and identifying parameters for flexible industrial building design and production planning. However, a holistic summary of all relevant parameters in IIBD is lacking.

2.3. Data and Model Integration

Integrated planning in industrial building design requires a high degree of networking, coupling and coordination of processes and discipline-specific models for all involved stakeholders, leading to increased complexity. Woodhead, et al. [64] see data integration as the key factor for value creation and a need to overcome the tendency to use point solutions in construction industry. However, the goal of seamless global software interoperability in construction industry is far from being achieved [65]. The application of Building Information Modelling (BIM) bears the potential to support integrated production and building planning [1]. BIM is seen as catalyst to bring more innovation and integration in the building sector, which is still caught in silo-thinking and sequential processes. BIM can be defined as a planning tool, but more over as a planning method and modelling process. BIM addresses both geometrical- and non-geometrical data (i.e., costs, technical properties) and aims to support data exchange within an interdisciplinary planning process [66]. BIM offers a common digital knowledge platform integrating the activities of all stakeholders along the construction value chain through improved communication and coordination between stakeholders [67,68]. BIM and computer-aided simulations are already used in isolated cases, but the applications are still in classical domain-specific thinking and silo attitude of the data of the different planning disciplines, resulting in information and data losses [69]. Moreover, the integration of production planning and building design is a major challenge for BIM processes and tools [14], as there has been little research on BIM applications and workflows, interfaces and data exchange with other related departments in manufacturing companies [13]. Currently, building and production planning processes run sequentially and neglect discipline-specific interactions [70]. Major obstacles in integrating building and production planning models and processes are due to missing maturity level specifications and missing data management standards [27]. Some researchers focus on the integration of factory planning processes such as the managing of interdependencies and information of different tasks [70–73], the overall project management using component-based synthesis [74] or the integration of production planning into BIM-based building models for the operation phase [75,76]. The literature review shows that there are many research efforts on digital integration of industrial building design and production planning methods. Despite the fact that the integration of discipline-specific data and models could support decision-making and lead to improvement performance, there is currently a lack of holistic integration in IIBD.

2.4. Decision-Making Support in IIBD

Decisions made at early design stage, such as during the program and schematic design stages, have a major impact on the building performance and one need to develop design alternatives, which must be evaluated, refined, evolved and finally optimized early on [77]. Furthermore, decisions on building flexibility [78] and manufacturing flexibility [29] are more impactful when made at early design stage. An integrated design approach where all systems and components work together can lead to well-designed and cost-effective buildings, improving the overall functionality and environmental performance. Decision-making in design entails the process of generating, evaluating, and determining design alternatives to satisfy given requirements or criteria [79]. In IIBD, stakeholders are faced with the choice of multiple conflicting parameters and a vast number of complex design decisions, highlighting the need of guided decision support. The factory planning process needs quantitative evaluation of designs and systematic decision support [80]. A holistic digital factory model builds upon three fundamental components: a target setting/calculation model, a heterogeneous data integration and sufficient decision support [71]. Numerous research studies have been conducted regarding optimization and decision-support tools for manufacturing systems. Büscher et al. [28] presented the concept of virtual production intelligence for an integrative information system, enabling planners to integrate, to aggregate and to analyze data gathered during planning projects. Francalanza et al. [29] developed a knowledge-based decision-making approach for designing changeable manufacturing systems. Kluczek [33] presented an MCDM approach to assess the sustainability of manufacturing processes and Mousavi et al. [30] demonstrate an integrated approach for improving energy efficiency of manufacturing process chains. Hawer et al. [72] develop a process model taking into account data-based interdependencies in factory planning and adopted a modular approach, including one module respecting the factor building. Dallasega et al. [4] investigated Industry 4.0 as an enabler of proximity for construction supply chains within a systematic literature review. The above-mentioned research is remarkable; however, it fails to fully incorporate building design. Based on the conducted research on building level, several authors proposed models concentrating on the industrial building itself. Kovacic et al. [34] developed an economic and environmental life-cycle analysis tool for facade-systems of industrial buildings and state that long-term horizons in the decision-making process are necessary. Heravi et al. [59] focused on social, economic and environmental aspects of industrial buildings and developed a MCDM framework for selection of optimized sustainable industrial building options. Cuadrado, et al. [81] proposed a MCDM sustainability assessment of industrial buildings including environmental, economic and social factors, as well as other factors (employee safety, corporate image), however neglect production processes. Chen et al. [39] integrate sustainability into the factory planning process, developing a model describing relations between factory buildings, manufacturing equipment, sustainability aspects and process planning. Bleicher et al. [37] proposed a co-simulation tool for predicting the energy demand of production facilities in early design stage, integrating sub-systems and Chinese et al. [82] used a multi-criteria analysis to select space-heating systems in industrial buildings. Gourlis and Kovacic [38] analyzed the building envelope refurbishment of an existing industrial facility using BIM and identify critical parameters affecting the energy performance. The above-presented research on optimization and decision support in IIBD is remarkable, yet it focuses on either production system or building optimization and neglects a holistic approach.

In summary, BIM, digital design and optimization methods for IIBD are already used in isolated cases, but there is still a lack of interoperability and data consistency between discipline-specific tools. A large number of interrelated processes and data, sub-processes and stakeholders involved in different project phases make IIBD complex. Holistic industrial building design requires maximum stakeholder and software integration, including a vast amount of parameters from production planning, structural design, architecture and energy planning already at early design stage. However, few researchers have examined methods that explore holistic design guidance in IIBD for the needs of Industry 4.0.

This paper is addressing the collection of data to develop a formal design guideline for IIBD towards the requirements of Industry 4.0, focusing on the three levels of: objectives, technical parameters and the planning process in IIBD. The data were gathered trough a multiple case study based on expert interviews. The literature research provided us with numerous parameters and the latest findings in industrial building design and production planning to expand and complete the developed design guideline. The followed methodology is described in the next section.

3. Methodology

The employed methodological approach is based on social empirical research, conducting a comprehensive literature review and a case study methodology with expert interviews [83]. The literature review served to analyze best practices in industrial building design and production planning, while the multiple case study with expert interviews was performed to close the knowledge gaps of the researchers and to generate technical and process knowledge [84]. Figure 1 presents the overview of the research methodology and the research outputs.

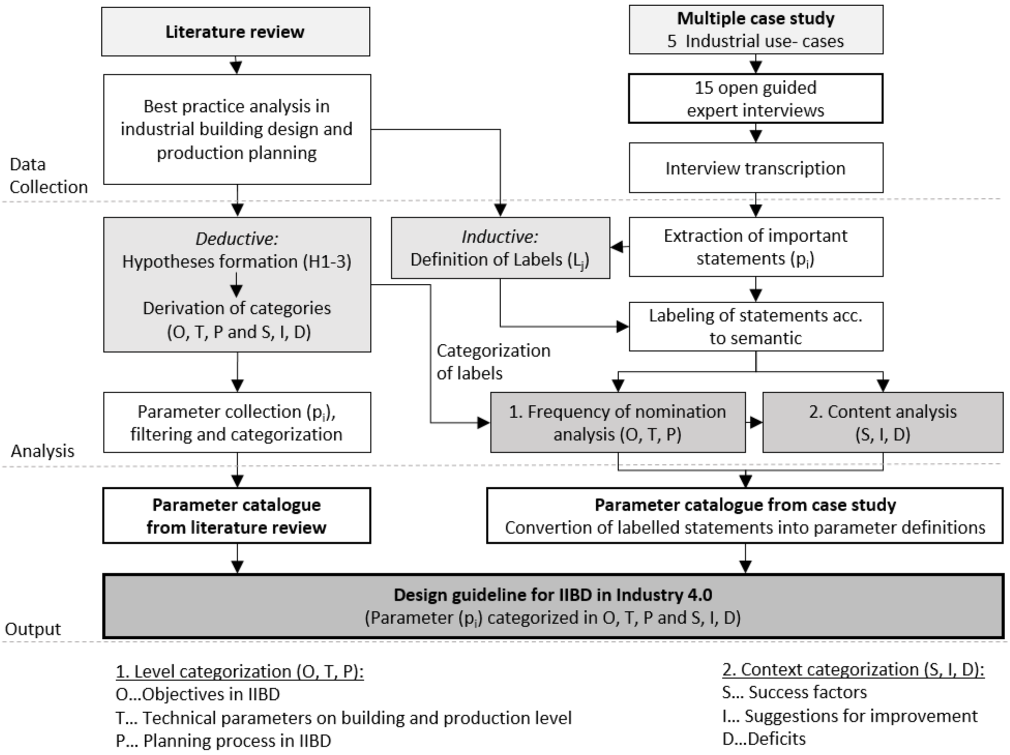

Figure 1. Overview of the research methodology and scope of the paper.

Based on the literature review findings, the three hypotheses (H1—Flexibility, H2—Structural design, H3—Integrated computational models), presented in Section 1, were formulated and two categorization schemes (level and context categorization) defined. The categorization served us for analysis, filtering and classifying the obtained parameters into a transparent structured design guideline.

The level categorization (O, T, P) arranges the parameters into the three categories of objectives level (O) resulting from hypothesis 1, technical parameters level (T) formed from hypothesis 2 and planning process level (P) following hypothesis 3.

- **O.** Objectives in IIBD.
- **T.** Technical parameters on industrial building and production level.
- **P.** Priorities, potentials and problems in the planning process of industrial buildings.

The context categorization (S, I, D) describes in which context the parameters are identified. Through a content analysis of the interviews conducted [84], the parameters are classified according to the expert statements into the categories of Success factors (S), Suggestions for improvement (I) and Deficits (D).

The interview evaluation followed the procedure of Bogner et al. [84] by labelling of the received statements in order to develop a plausible and theoretically sophisticated reading of expert practices in the best possible directness. Thereby, after the transcription of the interviews, a list of all relevant statements was compiled in a Microsoft Excel spreadsheet. According to the semantic structure and core content, each statement was allocated to a label (L_j), following an inductive "bottom-up" logic, see Section 3.1. The labelling of text fragments was necessary to make individual statements countable and comparable. First, a frequency of nomination analysis was carried out, sorting the labels by number of mentions per stakeholder. Second, a content analysis was conducted to describe in which context the labelled statements were identified.

For the design guideline development, the labelled statements were concretized into parameter definitions (p_i). The parameter catalogue is structured in matrix form, classifying each parameter to one level and one context category (see Equation (1)). Equation (1) describes a parameter whose underlying statements were labelled within the label number 17, were made on planning process level and were named in context of a success factor. Finally, the interview analysis results were verified and extended by the literature research results, completing the design guideline for IIBD in Industry 4.0 which is categorized into O, T, P and S, I, D.

$$p_i \rightarrow Label_j \rightarrow \begin{pmatrix} \mathsf{O} & \mathsf{S} \\ \mathsf{T} & \mathsf{I} \\ \mathsf{P} & \mathsf{D} \end{pmatrix};\ p_8 \rightarrow Label_{17} \rightarrow \begin{pmatrix} 0 & 1 \\ 1 & 0 \\ 0 & 0 \end{pmatrix} \tag{1}$$

3.1. Case Study Design and Definition of Labels

A multiple case study methodology with expert interviews was carried out in this study [83]. The interviews conducted with experts from the industry allowed the mapping of discipline-specific knowledge, needs and requirements in industrial building design practice focusing on Industry 4.0 aspects. Thereby, fifteen experts (five building owners, three architects, three structural engineers and four production planners) involved in five real industrial building projects, were interviewed via guided, open-ended interviews. Regarding the number of use cases to be investigated, we followed the recommendation of four to ten use cases to study [83]. The use cases were selected because they had the best accessibility to leading stakeholders. In industrial context, the availability of data is difficult because of industrial espionage. In this study, our industrial partners agreed to provide data and information from five real use cases from the production sector. When selecting the use cases, it was important to examine different types of production so as not to obtain results only for a specific production sector. Table 1 presents the use-cases involved in the study and the number of conducted expert interviews per use-case and stakeholder.

Table 1. Overview of the use cases and conducted expert interviews.

Use Cases	**A**	**B**	**C**	**D**	**E**
Production Type	Cleanroom-Chip	Metal processing	Metal processing	Food production	Food production
Gross Floor Area [m^2]	60,000	16,000	9000	24,000	4600
Total Building Costs [mil]	n.m.	45	17	50	n.m.
Interviews per Use-Case	**A**	**B**	**C**	**D**	**E**
1 Building Owner	1	1	1	1	1
2 Architect	0	1	1	0	1
3 Structural Engineer	0	0	1	1	1
4 Production Planner	0	1	1	1	1

The guided interviews were supported by an open-ended questionnaire. The questionnaire included questions about general personal and company information, about the specific use-cases and about the planning process, goals and potentials in Industry 4.0. The questionnaire structuring and the contained questions are presented in Table 2.

After the transcription of the interviews, the expert statements were allocated to labels in order to analyze the interview results. Table 3 presents the defined labels with given examples of involved statements. The labels were grouped according to the level categorization of O, T, P. On objectives level eight labels, on technical parameters level four labels and on planning process level ten labels were defined.

Table 2. Questionnaire for the guided, open-ended expert interviews within the case study.

1. Questions about General Personal and Company Information:
1.1 What discipline/profession do you belong to/what role do you usually play in projects/years of experience?
1.2 Information about the company: fields of activity/company size/general project sizes/production type.
2. Questions about the Use-Case:
2.1 Company organization: size and organization of team/process organization and coordination/interfaces.
2.2 Contract form and commissioning within the project/criteria for commissioning.
2.3 Describe the planning process: working methods/application of digital tools/data collection and exchange
2.4 Describe the communication, collaboration and exchange of information (internally and externally) within the project.
2.5 Describe the main deficits and potentials in the projects planning process and interdependencies to other disciplines.
3. Questions about Ideal Industrial Building Design Processes and Goals of Industry 4.0:
3.1 Describe an ideal planning process and requirements of successful industrial building design for Industry 4.0.
3.2 What are key criteria and goals in industrial building design for the needs of Industry 4.0?
3.3 What are successful (future) digitization and knowledge management strategies in industrial building design?

Table 3. Overview of the label structuring per level categorization for analysis and highlights some statement examples received from the expert interviews.

O. Labels	**O. Objectives Level (e.g., Statements)**
Architectural quality	Aesthetic, functional, sustainable buildings
Communication	Layouts which allow communication, collaboration and information flow
Costs	Design to cost, minimize life cycle costs
Durability	Robust buildings which can accommodate to changes, robust structures and materials
Expandability	Plan growth areas in buildings, production and on properties
Flexibility	Allow reconfigurable machine layouts in buildings (e.g., maximum span width)
Lean Production	Enable constant production re-organization, pull principle, no reservation of capacities
Energy Efficiency	Efficient heating and cooling, facade and roof insulation, sound insulation, draught
T. Labels	**T. Technical Parameters Level (e.g., Statements)**
Architecture	Floor plan design, room height, daylight, building envelope, traffic areas for production
Building Service Equ.	Type, geometry and position of media supply, installation level, fire safety
Production Planning	Type of production line (U-,S-, I production), production process, machine types and layout
Structural Design	Column axis grid, foundation, structural type, span width, material, consider retrofitting loads
P. Labels	**P. Planning Process Level (e.g., Statements)**
3D Planning	3D planning and models for better collision checks, presentation and visualization support
Commissioning	Architectural contests, commissioning of a general planner, consulting for client
Communication	Early communication of client and stakeholder goals, standardized and open communication
Design Team	Small, competent and versatile design teams, BIM manager
Flexibility in Design	Integration of flexibility measures for decision support, create awareness for flexible design
Early Design Stage	Early integration of construction firm and structural design, early definition of goals
Integrated Design	Process and model integration, follow joint goals, quick feedback loops
Interfaces	Different interfaces, data and software between building and production planning
Requirement planning	Demand planning and holistic understanding of processes, definition of expectations
Software	Challenging model and data exchange with other disciplines, no holistic design platform

4. Case Study Analysis

In this section, we present the results of the frequency of nomination analysis and the content analysis of the statements received from the expert interviews.

4.1. Frequency of Nomination Analysis

After the interview transcription, followed by the extraction and summarization of the relevant statements and the subsequent assignment of the statements to a label, an analysis of the labels by frequency of nomination was carried out. The analysis results are organized according to the labelling structure into objectives, technical parameters and planning process level. The frequency of nomination (F) of a label is determined by the total number of statements allocated to a label divided by the total sum of labelled statements in the respective O, T, or P category, see equation 2. Furthermore, to obtain an indication of the average mentions of the label per interviewed expert ($n = 15$), the mean value (μ) is determined, see equation 3. The Table 2 (for O), Table 3 (for T) and Table 4 (for P) present the number of statements made according to a label per stakeholder, F and μ.

$$F_i = (\text{Sum of all statements allocated to a label } L_i)/(\text{Sum of all labelled statements in a category (O, T, P)}) \quad (2)$$

$$\mu_i = (\text{Sum of all statements allocated to a label } L_i)/(\text{Sum of all interviewed experts } (n = 15)) \quad (3)$$

4.1.1. O. Objectives Level

Table 4 presents the frequency of nomination analysis results on objectives level categorized per stakeholder. The results reveal that most statements in the category of objectives in IIBD are related to flexibility (F = 42%). In particular, the building owners highlight the importance of designing flexible buildings and production systems. The analysis shows that the second most nominated objective is expandability (F = 14%) followed by lean production (F = 12%) and architectural quality (F = 11%). Communication counts five statements (F = 8%) and costs four statements (F = 6%), both mentioned from building owners and production planners. The energy efficiency (F = 5%) and the durability (F = 3%) are further objectives in IIBD. The interviewed architects consider flexibility, expandability and the architectural quality as main objectives, while the structural engineers seek for flexibility and increased durability of the supporting structure in design. The production planners define lean production, flexibility and expandability as goals in IIBD.

Table 4. O. Objectives level: Frequency of nomination (F) of the labels on objective level categorized per stakeholder.

Label (O)	Building Owner	Architect	Structural Engineer	Production Planner	F	μ
Flexibility	18	4	2	3	42%	1.8
Expandability	5	2	0	2	14%	0.6
Lean Production	4	0	0	4	12%	0.5
Architectural Quality	4	2	0	1	11%	0.5
Communication	4	0	0	1	8%	0.3
Costs	3	0	0	1	6%	0.3
Energy Efficiency	2	0	0	1	5%	0.2
Durability	1	0	1	0	3%	0.1
		Σ	Statements (n)	65	100.00%	

4.1.2. T. Technical Parameters Level

Table 5 presents the frequency of nomination analysis results on technical parameters level. Twelve out of thirty-one statements can be allocated to the label of structural design (F = 39%), followed by eleven mentioned parameters within the label architectural design (F = 35%). Building service equipment parameters are especially highlighted by building owners (F = 13%) and production planning parameters (F = 13%) are mentioned by building owners and production planner. Building owners relate five statements to parameters in structural design for flexible industrial buildings. The architects see significant parameters in industrial building design within the label architecture (number of mentions (n) = 2) and structural design (n = 1). Structural engineers bring up five statements, including structural design parameters followed by two architectural design parameters. The production planners aim for free floor plans in architectural design (n = 5) to allow reconfiguration of production layouts in production planning (n = 3).

Table 5. T. Technical Parameters: Frequency of nomination (F) of the labels on parameters level categorized per stakeholder.

Label (T)	Building Owner	Architect	Structural Engineer	Production Planner	F	μ
Structural Design	5	1	6	0	39%	0.8
Architecture	2	2	2	5	35%	0.7
Building Service Equipment	4	0	0	0	13%	0.3
Production Planning	1	0	0	3	13%	0.3
		Σ	Statements (n)	31	100.00%	

4.1.3. P. Planning Process Level

The frequency of nomination analysis results on planning process level (see Table 6) demonstrate that most statements refer to the focus on the early design stage (F = 16%) for successful IIBD processes. The second most nominations mention sufficient interfaces (F = 14%) and the constellation and skills of the design team (F = 13%). The applied software environment (F = 13%) is considered as another significant aspect among all stakeholders. An integrated design approach (F = 12%) was mentioned multiple times from building owners, structural engineers and production planners. Furthermore, flexibility in design (10%) and 3D Planning (F = 7%) are stated as requirements for effective industrial building design processes. Finally, requirement planning (F = 6%) and commissioning (F = 3%) do affect industrial building design processes according to the provided statements. The building owners mostly relate their statements on planning process level to interfaces (n = 8), integrated design (n = 8) and flexibility in design (n = 7). Architects see the focus on early design stage (n = 6) and the software environment (n = 5) as major aspects for a projects' successes. The structural engineers make statements regarding the labels' interfaces (n = 12) and the design team constellation (n = 11), followed by the focus on early design stage (n = 6) and software (n = 6). The most statements from production planners refer to the focus in early design stage (n = 8), software (n = 7) and flexibility in design (n = 7).

Table 6. P. Planning process level: Frequency of nomination (F) of the labels on process level categorized per stakeholder.

Label (P)	Building Owner	Architect	Structural Engineer	Production Planner	F	μ
Focus Early Design Stage	6	6	6	8	16%	1.7
Interfaces	8	1	12	2	14%	1.5
Design Team	1	4	11	5	13%	1.4
Software	3	5	6	7	13%	1.4
Integrated Design	8	1	5	6	12%	1.3
Flexibility in Design	7	0	2	7	10%	1.1
3D Planning	4	2	3	2	7%	0.7
Communication	3	4	2	0	6%	0.6
Requirement Planning	2	4	0	4	6%	0.7
Commissioning	1	3	0	0	2%	0.3
		Σ	Statements (n)	161	100.00%	

4.1.4. Summary of the Frequency of Nomination Analysis

In total, 65 statements were identified as objectives, 31 statements were allocated to technical parameters and 161 statements were recognized regarding the planning process. Figure 2 presents the relative frequency of nominations of the labels in the form of pareto front diagrams. The diagrams contain both bars and lines, where the individual labels are represented in descending order by bars, and the cumulative total of the sample is represented by the curved red line. The pareto principle can be seen as a powerful decision-making criterion and states that the bulk of problems are the result of a few factors. Thus, to gain the largest benefits for quality and productivity improvement, the focus should be on the "vital few" as opposed to the "trivial many" [85]. The first diagram presented in Figure 2 demonstrates that the largest frequency of occurrence for objectives in IIBD is on the label flexibility (27 statements) with the largest bar, followed by expandability with 9 statements. The two most vital labels on technical parameters level are structural design with 12 statements and architectural parameters with 11 coded statements. On the planning process level, the vital statements on the pareto front are the focus on early design stage (26 statements), interfaces (23 statements), the design team (21 statements), software (21 statements) and integrated design (20 statements).

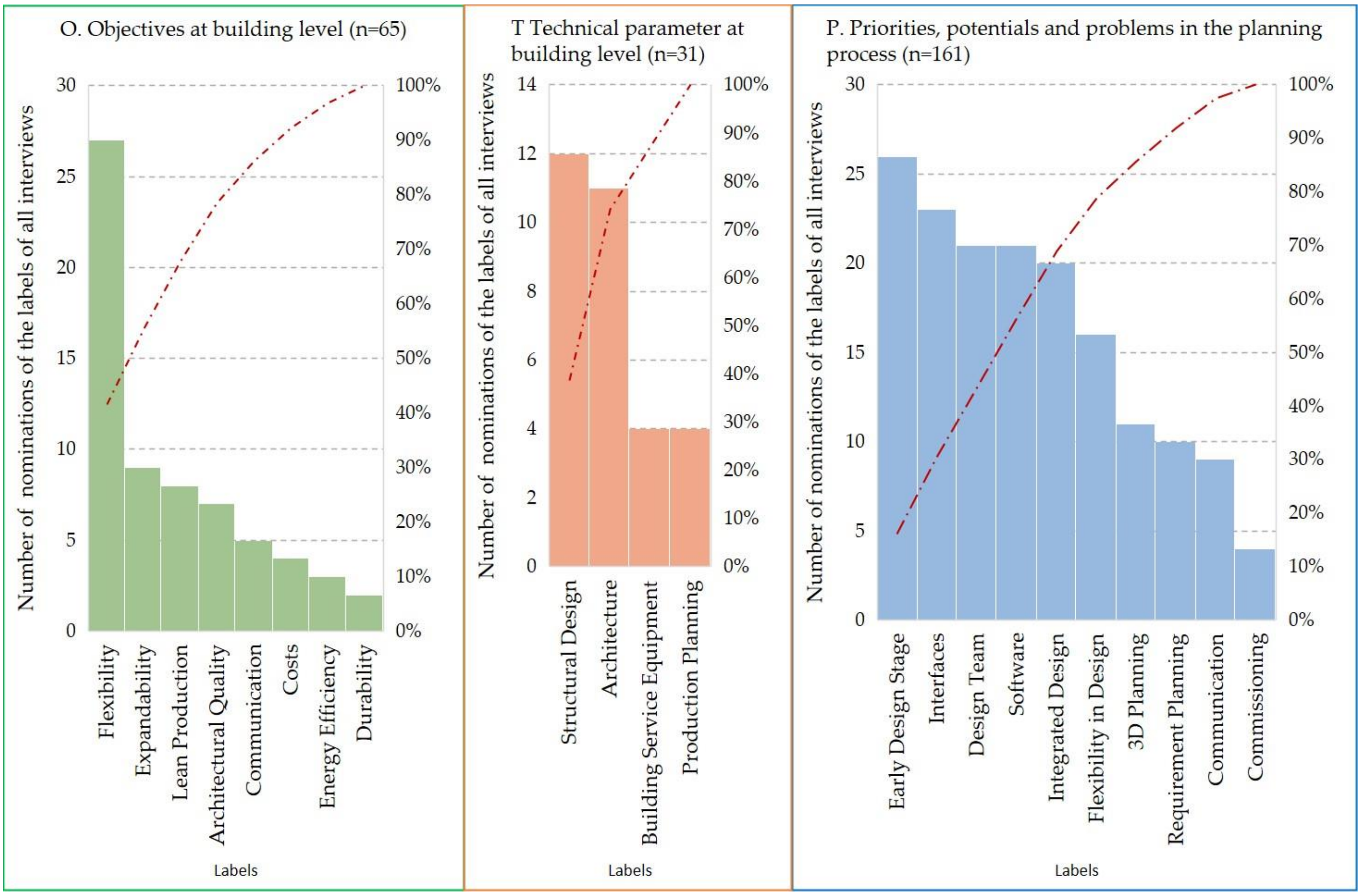

Figure 2. Frequency of nomination analysis results of the labelled expert statements on objectives, technical parameters and planning process level in form of pareto front diagrams. The labels are represented in descending order by bars and the cumulative total of the label sample is represented by the curved red line.

4.2. Content Analysis

This section presents the results of the content analysis, examining the context in which the statements were made and to determine whether a label belongs to a success factor, a suggestion for improvement or a deficit. The analysis is a deductive conclusion and does not represent an evaluation. A statement with a corresponding label in connection with i.e., a deficit, cannot assure that it is actually a deficit for all stakeholders as naturally goals can be conflicting among different stakeholders. Table 7 presents the content analysis results and the deductive categorization of the labels sorted by the mean value of the label mentioned per stakeholder.

4.2.1. S. Success Factors

The labels, thus included parameters extracted from the statements, identified as success factors have the potential to meet objectives and increase performance improvement in IIBD for Industry 4.0. On objectives level, the statements related to flexibility, lean production, architectural quality and communication were recognized as potential success factors. The content analysis of the statements on technical parameters level shows that the labels structural design and production planning can be defined as success factors. The load-bearing structure and production systems have a high impact on flexibility, thus are important prerequisites for sustainable industrial building design. The content analysis of the statements allocated to the labels on planning process level reveals that the labels focus on early design stage, integrated design and 3D planning were made in context to a success factor.

4.2.2. I. Suggestions for Improvement

The content analysis on objective level reveals that suggestions for improvement level are stated within the labels of expandability, costs, durability and energy efficiency. The expert interviews reveal that the expandability of building and production areas is an important goal but often not realized in practice yet. Most of the time “slim fit” buildings are build, according to current production demands. If the design team would plan for growth areas (i.e., build one more axis grid) the business growth could correlate to the building service life. The statement analysis further reveals that currently buildings are not designed for sufficient robustness but increasing the durability of the supporting structure would allow better adaption to different use scenarios.

According to the content analysis on a technical parameters level, the architectural parameters have potentials for improvement, suggesting to focus on the maximization of the inner room height and to design the building for the current and future machine and production layout demands. In addition, the design of industrial buildings could be improved by making them suitable for automation processes, i.e., enabling driverless systems by providing more robust floors and avoiding steep ramps and narrow paths. The analyzed statements suggest an improvement of the building service parameters. It is recommended to always decouple them from the building structure to ensure a flexible media flow, thus allow flexible machine layouts. In addition, the media supply should be oversized for future retrofitting.

Suggestions for improvement on planning process level concern the design team. The design team should work with smaller teams and versatile team constellations and need precise coordination. In addition, it is recommended that all involved stakeholders must be familiar with the holistic project goals, pursuing them throughout the whole planning process to overcome silo thinking. The opinion among the interviewed experts is that currently flexibility measurements are not integrated into the planning process. However, creating awareness for flexibility to all stakeholder and providing flexibility measures as decision support at early design stage could improve the performance of a building in long term. Furthermore, the experts state that the communication culture must be improved and suggest standardized, open communication processes to improve the design process, thus project outcome.

4.2.3. D. Deficits

The content analysis reveals four deficits in current IIBD practice. The interfaces between building and production planning and from 2D to 3D software are inefficient and related with data loss. Furthermore, different stakeholders work with different levels of detail (LOD) and different closed software systems, making the data and information exchange challenging. The lack of a holistic factory design software to be able to see the effects of a planning decision on other disciplines design (i.e., allow quick collision checks) was highlighted by the experts. Moreover, the interview participants see deficits in requirement planning and commissioning. Usually, not all planning stakeholders are involved in the planning process from the very beginning, starting with the master planning. In addition, there is a lack of early communication and awareness of joint project goals that all planning disciplines should adhere to and follow throughout design and construction.

Table 7. Content analysis results: The table presents the context categorization of the labels according to the core content of the included statements into success factors, suggestions for improvement and deficits, sorting them by the mean value of the label mentioned per stakeholder.

	S. Success Factors	
(Level) Label	**Summary**	**μ**
(O.) Flexibility	Flexible buildings which allow reconfigurable layouts and processes	1.80
(P.) Early Design Stage	Integration, collaboration and definition of goals already at early design stage	1.73
(P.) Integrated Design	Stakeholder cooperation throughout all stages; Integration of building and production	1.33
(T.) Structural Design	Design of over-capacity of the structure to enable retrofitting and expansion	0.80
(P.) 3D Planning	3D planning for collision checks (structure, media, machines) and visualization	0.73
(O.) Lean Production	Enable reconfiguration of machines; No reservation of capacities; Pull principle	0.53
(O.) Architectural Quality	Design of aesthetic, representative, sustainable and functional buildings	0.47
(O.) Communication	Communication should be enabled throughout the whole building and layout	0.33
(T.) Production Planning	Respect production process in building design; Production flow; Machine types/size	0.27
	I. Suggestions for Improvement	
(Level) Label	**Summary**	**μ**
(P.) Design Team	Small, competent and versatile project team; Software know-how; Follow joint goals	1.40
(P.) Flexibility in Design	Early integration of flexibility measures; Create awareness for flexibility	1.07
(T.) Architecture	Floor plan design; Room height; Design for automation; path and walkway planning through the production process	0.80
(P.) Communication	Improve communication culture; Standardized and open communication; Mediation	0.60
(O.) Expandability	Expansion areas in building, production and on property to enable business growth	0.53
(T.) Building Service Equ.	Customization of media supply; Flexible media flow; Decouple media and structure	0.27
(O.) Costs	Design to cost; Respect and minimize life-cycle costs in design stage	0.27
(O.) Durability	Design robust buildings/structures to enable changes; Prolong building service life	0.20
(O.) Energy Efficiency	Efficient air supply and exhaust; Cooling/heating; Sound insulation; Enclosure system	0.13
	D. Deficits	
(Level) Label	**Summary**	**μ**
(P.) Interfaces	Inefficient interfaces from 2D to 3D and building to production models; Data loss at exchange; Different level of details	1.53
(P.) Software	Improve discipline-specific data exchange; No holistic factory design software	1.40
(P.) Requirement Planning	Early communication of requirements and goals for a holistic process understanding	0.67
(P.) Commissioning	Architectural competitions; early commission of all stakeholders; General planner	0.27

5. Result—Design Guideline for IIBD in Industry 4.0

Hence, as final result, we summarize and merge the case study and literature review findings and present a design guideline for IIBD in Industry 4.0. Therefore, the expert statements were abstracted into parameter definitions and the design guideline for IIBD in Industry 4.0 was developed in the form of a categorized parameter catalogue in a Microsoft Excel spreadsheet. The parameter catalogue maintains the structuring of the level categorization (O, T, P), the context categorization (S, I, D) and the label allocation.

In total, the design guideline consists of 129 identified parameters. Of those, 36 parameters were allocated to objectives, 24 to technical parameters and 69 to the planning process. Table 8 presents an exemplary structure of the design guideline table, where each parameter in O, T, P is associated with a label and a context. The parameter value corresponds to the content analysis of the statements of the interviews and/or the conclusion of the literature sources.

Table 8. Exemplary table extraction of the design guideline for IIBD in Industry 4.0. The table shows the structuring of the parameters: First, the parameters are categorized into objectives, technical parameters and process level in adherence to the label assignment. Second, the parameters are indicated as a success factors, a suggestions for improvement or a deficits.

Design Guideline for IIBD in Industry 4.0						
O. Objectives in integrated industrial building design.					Data source	
Label	Context	H	Parameter	Value	Use-Case/Expert	Literature
Flexibility	S	O1	Column free- zones in production area	Minimize amount of columns inside production layout area	[C1]	[19,41]
		O2	Flexible machine layout	Spatial change of machines	[B1] [C1] [C4]	[19,52,63]
Expandability	I	O20	Maximize growth areas	Expansion possibility through predefined growth areas in production, building, property	[D1] [E4] [C1] [C4]	[19,41,81]
		O21	Pre-planning of expansion interfaces	Provide and pre-design interfaces for future expansions	[D4]	[23]
T. Technical parameters on industrial building level						
Structural Design	S	T1	Foundation	Oversize foundation for future loads	[B2]	[19,63]
		T2	Girder span width	Maximize column grid distance	[C1]	[19,63]
Architecture	I	T7	Free inner room height	Surplus of room height for retrofits	[B4] [E1] [E3]	[19,41,60]
		T8	Floor plan configuration	Prefer orthogonal floor plans and avoid special shapes	[E5]	[38,41]
P. Priorities, potentials and problems in the planning process of industrial buildings						
Focus early design stage	S	P1	Early needs assessment	Early integration of stakeholder needs	[B2]	[1,11,77]
		P2	Early BIM Collaboration	Holistic BIM model at early design stage	[C3] [D3]	[1,27]
Interfaces	D	P15	Definition of Interfaces	Enable sufficient interfaces for data and model exchange	[C2]	[13,52,73]
		P16	Digital language and LOD	Avoid different digital speeches (decide if 2D or 3D)	[D1]	[11,27,66,67]
Design Team	I	P27	Knowledge transfer	Experienced team members with a lot of personal contact/collaboration	[E3]	[55,56,68,86]
		P28	Team members	Deployment of people with visions and increased experience level	[C3]	[11,27,56,86]

The following is a summarized description of the design guideline parameters identified from the case study and literature review:

5.1. Objective Level Parameters

In total, 36 parameters could be identified within the eight labels on objectives level:

Flexibility was identified as the primary objective in IIBD for the interview participants and includes parameters such as reconfigurable machine layouts, flexible working stations and production areas that provide puffer zones. Further flexibility-related goals are a maximum free gross floor area, maximum span width with no columns inside the production area, a maximum inner hall height and the maximum process variability to enable multiple different production process scenarios in the building. Building service equipment, which is intelligently adaptable to changing machine layouts, modular construction and facades with increased openings to allow the latter adding of machines were also mentioned as objectives to increase flexibility.

Architectural quality related objectives were identified as aesthetics, maximum exposure surfaces to increase the working atmosphere and the application of sustainable, high-quality materials within design. Furthermore, a functional shape and modularity in construction are important goals for the experts towards increased architectural quality.

Expandability-linked objectives for the interviewed stakeholders are the maximization of growth areas and surplus of available floor space for expansion possibility of the building, the production and the property. Expansion should be designed with the possibility to extend production during full operation. Moreover, stakeholders recommend an early planning of expansion interfaces (i.e., expansion possibilities of structural and technical building service equipment) and evaluating the expansion capacity of the property already when purchasing new land.

Lean production was identified as the main goal for the production planners, aiming for a harmonization of need and demand in production planning. Thereby, avoiding intermediate storage in the production flow and separating value creation from logistic processes. The production capacity should follow the pull principle, avoiding capacity peaks.

Communication must be promoted throughout the whole layout and building. For effective communication and collaboration, the interview participants recommend the optimization of the positioning of building and production units. The goal is to locate production and office buildings as close as possible.

Cost goals should follow the concept design to cost and the main objective mentioned by the experts is to minimize the life-cycle costs for improved economic performance.

Durability of the building can be increased by a regular, robust and over-dimensioned load-bearing structure. The load-bearing structure's capacity must be designed to carry future loads for retrofitting or reconfiguration of production systems. Resistant buildings aim to reduce greenhouse gas emissions and the resource consumption by extending the buildings service life, thus avoiding rescheduling or demolition.

Energy efficiency can be improved by optimization of the air supply and exhaust, the insulation of the façade and roof systems and the whole building envelope system with window openings.

5.2. Technical Parameters

In total, 24 parameters were defined within the four labels on technical parameters level:

Structural design-related technical parameters mentioned by the experts are the material and construction type, load-bearing system type, dimensioning and position of girder, foundations and columns and the lateral system type. Furthermore, to guarantee a surplus of the inner hall height, results in minimizing of the girder height. However, to be able to add future loads, an over dimensioning of the structural elements (foundation, columns and girder) for increased load-bearing capacity should be provided.

Architectural parameters for an IIBD are the floor plan reconfiguration (avoid special shapes and prefer orthogonal, rectangular shapes), the façade system type and the lightning/window type, thus position. Moreover, experts state to design the ramp and path situation within the building concerning reconfigurable and changing production processes. Furthermore, they suggest to plan the inner free room height with additional surplus than the current machine layout requires.

Building service equipment parameters received from the interviews are the type and dimensioning of the energy media supply, the fire protection system and the position, distribution and customizability of the utilities. Additionally, experts recommend decoupling the distribution of the media from the structural system.

Production planning related parameters suggested by the experts are the central merging of machine data, the production process flow and the production process layout. Moreover, the interview participants recommend respecting the position and dimension of machines and the working and maintenance area around the machines for the planning of space requirements.

5.3. Planning Process Parameters

In total, 69 parameters were identified within the ten labels on planning process level:

The focus on early design stage label contains parameters, which are relevant for the early design stage in IIBD, including parameters such as early integration of structural design, machine layouts/sizes and different production process scenarios. Furthermore, the experts suggest carrying out an early need and goals assessment with all stakeholders and the early use and collaboration of Building Information Modeling (BIM) methods. The integration of all stakeholders including construction firms, already at master planning phase is recommended to improve the design process through increased transparency.

Interfaces related parameters mentioned by the stakeholders contain efficient interfaces amongst different stakeholder on process and model level, technological innovation integration and interoperability. Standardized exchange formats and a common digital language (decide if 2D or 3D) are prerequisites for efficient planning processes and require a well-defined coordination strategy, interface definitions and modeling guidelines. Furthermore, experts suggest the employment of a BIM-Manager.

Design Teams can improve the design process through a reliable project manager, an effective collaboration strategy and an increased experience level of the involved stakeholders. According to the experts, special discipline-specific knowledge should be exchanged and transferred through regular structured design meetings including all stakeholders. The interview partners suggest that the composition of the design team should be kept as small but versatile as possible.

Software environments in IIBD seek for the establishment of a holistic digital design platform and integrated digital models. The experts aim for software, which provides collision check and decision-making support between different domains to avoid multiple processing steps. The digital data transfer between discipline-specific software must be improved. The experts highlight the lack of a digital holistic factory design software.

Integrated design in industrial building design aims for close collaboration and data and information exchange between all disciplines in all project phases. Experts state that the integration of all disciplines needs sufficient process and model integration and should be also defined in contracts. Experts recommend a harmonization of production planning processes and models with building design processes and models.

Flexibility in design parameters mentioned by the interview participants relate to flexible design systems and flexible data exchange, the consideration of future developments already in early design stage, the awareness creation of flexibility amongst all stakeholders and the integration of flexibility measures for decision-making support.

3D planning should enable central collision checks of i.e., machines and building structure and improve visualization and presentation.

Communication related parameters in IIBD processes contain standardized communication procedures, communication of project reviews to learn from previous projects and the improvement of communication to build trust and open relationships between all stakeholders.

Requirement Planning is according to the expert statements essential in IIBD processes. The building owner needs to communicate goals and needs for the project success to all stakeholders already at requirement phase. A holistic project understanding and the process demands must be provided to all stakeholders for early order quality and joint commitment.

Commissioning is suggested by the experts to commission a general planner for improved holistic design. The interview participant recommend to balance the orders and to avoid one-sided commissioning relationships.

6. Discussion

Based on interviews with experts and analysis of literature, a novel set of parameters was identified. These parameters form a design guideline for IIBD in an Industry 4.0 environment. The analysis of the interviews reveal significant principles and opinions in industrial building design and enabled the definition of objectives, technical parameters and planning process requirements in IIBD. Moreover, the content analysis of the expert statements allowed the classification of the identified parameters into success factors, suggestions for improvement and deficits.

The results of the interviews emphasize the crucial role of flexibility for sustainable industrial building design. Flexibility is the single criterion that all stakeholders would share when identifying objectives in IIBD. Consistently with our Hypothesis 1, we found that the experts unanimously agree that flexible buildings must have the capability to enable reconfigurable machine layouts and changes in the production processes to avoid early rescheduling or demolitions. The prolongation of the buildings service life has a positive impact on sustainability. Implementing flexibility to improve sustainability has also been investigated in the field of manufacturing [15] and residential building design [17] while some researchers study sustainability indicators in industrial building design [8,62,81]. The lack of a consistent definition of flexibility metrics for IIBD calls for future research.

In accordance with the literature and our H2, the design parameters commonly recognized as success factors in IIBD mostly relate to the structural building system. Experts described parameters such as the material and load-bearing system type, the dimensioning and position of girders, foundations and columns, the lateral system type. Moreover, the stakeholders highlight the necessity to design structural elements with excess capacity in order to allow for future retrofitting. To enable reconfigurable and extendable machine layouts experts suggest to include surplus when designing the floor plan and determining the building height. Building owners and production planners see the integration of production planning parameters such as machine types, machine sizes and production planning layouts into building design as success factors. Results from previous studies matched some of the parameters obtained from the interviews, and found additional parameters such as modular production areas, specific utility routing requirements [19], sprinkler systems for fire safety [63], insulation values and solar collector coverage [61]. The results of this study complement previous research and combine discipline-specific parameters from building owners, structural design, architecture and production planning into one holistic framework. However, in this study, a gap arises in the fact that although research community is intensively investigating the energy performance of industrial buildings [18,37,61,82] no energy or media supply planners were interviewed. In further research, energy planners will be included in the survey and the parameter catalogue expanded. Finally, although the interview and literature analysis reveal the importance of the load-bearing structure in IIBD, an industrial building design model focusing on structural performance optimization is lacking.

The most frequently mentioned criteria on the planning process level are the focus on the early design stage, integrated design and 3D planning. Those parameters are recognized as success factors by all professions. The study findings lead us to approve H3, that an integrated planning approach supported by powerful computational tools is required in IIBD practice. However, when identifying the main deficits in current industrial building design processes, the interviewed stakeholders agree that the software and interfaces currently available have major shortcomings. Several stakeholders propose the potential of BIM-related tools for IIBD, yet highlighting the lack of integrated digital design models. Interfaces from 2D to 3D and from building to production models either are lacking, inefficient or associated with data loss. The experts aim for software which enables collision checks and decision-making support to avoid multiple processing steps. Belated involvement of all planning stakeholders and the early definition of joint goals for a holistic project understanding are further identified deficits. The interviewees see improvement potential in the early involvement of experienced and versatile team members, the early integration of flexibility measures and a transparent communication and information culture. The findings on process level are in line with existing research, which recommends data integration to overcome point solutions [64] and highlights the potential of BIM for manufacturing [13]. In industrial building design, stakeholders have to deal with more complex interrelated planning parameters compared to the design of residential or public buildings. Hence, integration in factory design is difficult due to error-prone and complex interfaces between building and production planning and the lack of maturity models [27]. Advanced modeling and simulation technologies, including BIM, parametric modeling, cloud-based simulation, and optimization algorithms have the potential for automated generation, evaluation, and optimization of multiple building design options [69]. There is a gap of digital solutions for quantitative planning success evaluation and systematic decision support models in factory planning [28]. Hence, the design of flexible industrial buildings requires a powerful computational model for multi-objective design optimization that integrates interdependent parameters and supports interdisciplinary decision-making. Such a holistic model is currently lacking and is the subject of our future research.

7. Conclusions

In the course of this paper, a design guideline for flexible industrial buildings integrating Industry 4.0 requirements was presented in the form of a categorized parameter catalogue. The research goal was to develop a common terminology and guidance to describe efficient design parameters and approaches to integrate production planning and building design. The study differs from previous research on industrial building and production planning as it aims to analyze and incorporate discipline-specific knowledge from building owners, architects, structural engineers and production planners into one holistic framework. Interviewing fifteen experts of the aforementioned domains which were involved in five real industrial building projects, enabled the collection of (O) objectives, (T) technical parameters and (P) planning process requirements in IIBD for Industry 4.0. Each defined parameter was identified based on a set of distinct expert statements. The grouping of these statements into labels allowed a frequency of nomination analysis, sorting the labels by number of mentions per stakeholder. Additionally, a content analysis aided to locate in which context the statements were made and served to classify the parameters into (S) success factors, (I) suggestions for improvement and (D) deficits. The literature review served to confirm our research findings and to expand the design guideline with additional parameters. The developed design guideline for IIBD in Industry 4.0 serves as an agile document and auxiliary tool, which is easily expandable and can always be enriched with future knowledge enhancement.

The research results provided evidence for the formulated hypotheses that the realization of sustainable industrial buildings is enabled by flexible supporting structures to accommodate fast-moving processes in Industry 4.0. An integrated design approach supported by powerful computational tools is required as industrial building design involves complex interdependencies between interdisciplinary parameters. The presented research identifies the lack of a standardized IIBD approach to realize flexible industrial buildings respecting Industry 4.0 needs already at early design stage, to move the industry towards increased sustainability. The study captures the complex industrial building design process and provides in addition to theoretical support a reference point for future research or developments. With the provided understanding, building owners, designers and engineers can begin to identify underlying design choices and approaches that enable integration and better understand the needs of industrial buildings incorporating Industry 4.0 processes. The developed design guidance provides a basis of transparency for decision-makers to not only follow their own design decision rules. The essence of the proposed parameter catalogue is indeed to go beyond defining one solution. The results of the study underline the need for multi-objective optimization models in IIBD since no single metric or objective can adequately describe the holistic distribution of industrial building design performances. The design guideline can serve as principle requirement framework to build such digital systems and highlights common objectives and parameters in IIBD. However, a limitation of the study is that the formal design guidance does not concentrate on the parameter dependencies and the mathematical formulation of objectives. Future research should evaluate the direction and degree of interactions among the parameters to enable variables causal relationship analysis including the level of interactive influence among them. Furthermore, in the presented study, the experts interviewed were involved in industrial building projects from the cleanroom chip, metal processing and food production sectors. To refine the design guideline and gain deeper insights into impacts of different production types on building designs, more production sectors such as paper production, glass production and chemical processes should be investigated and evaluated. Another limitation is that energy planners were not included in this survey, which will be addressed in future research to extend the design guideline.

By identifying the underlying parameters, the categorized design guideline provides a means to describe coherent flexible industrial buildings for Industry 4.0. With the categories presented in this study, the building design and manufacturing industries can begin to standardize their processes and implement flexibility early in the design process. Hence, the study promotes awareness of the importance of flexibility to achieve sustainability and will support design decisions of building owners and planners towards extended industrial building life cycles. In conclusion, this research can be seen as an important milestone towards both integration of building design and production planning as well as a more holistic assessment of sustainability. The obtained results are considered of great practical significance, as building owners, production firms, architects and engineers can efficiently visualize the complex aspects surrounding industrial building design processes in Industry 4.0 environments.

The presented results set the goal for our future research, in which we aim to develop an integrated design approach and a multi-objective optimization and decision support model for automated design and visualization in virtual reality for flexible industrial buildings. Thus, we aim to place the load-bearing structure in the center of the optimization in order to improve the buildings flexibility. Follow-up studies to implement the parameters in a multi-objective optimization and decision support model will also contribute to further validate the proposed data.

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References

1. Oesterreich, T.D.; Teuteberg, F. Understanding the implications of digitisation and automation in the context of Industry 4.0: A triangulation approach and elements of a research agenda for the construction industry. *Comput. Ind.* **2016**, *83*, 121–139. [CrossRef]
2. Xu, L.D.; Xu, E.L.; Li, L. Industry 4.0: State of the art and future trends. *Int. J. Prod. Res.* **2018**, *56*, 2941–2962. [CrossRef]
3. Lasi, H.; Fettke, P.; Kemper, H.-G.; Feld, T.; Hoffmann, M. Industry 4.0. *Bus. Inf. Syst. Eng.* **2014**, *6*, 239–242. [CrossRef]
4. Dallasega, P.; Rauch, E.; Linder, C. Industry 4.0 as an enabler of proximity for construction supply chains: A systematic literature review. *Comput. Ind.* **2018**, *99*, 205–225. [CrossRef]
5. Oláh, J.; Aburumman, N.; Popp, J.; Khan, M.; Haddad, H.; Kitukutha, N. Impact of Industry 4.0 on environmental sustainability. *Sustainability* **2020**, *12*, 4674. [CrossRef]
6. *Climate Change: Status, Challenges, and Opportunities*; United Nations Environment Programme, Sustainable Buildings and Construction Initiative: Paris, France, 2007.
7. Röck, M.; Hollberg, A.; Habert, G.; Passer, A. LCA and BIM: Visualization of environmental potentials in building construction at early design stages. *Build. Environ.* **2018**, *140*, 153–161. [CrossRef]
8. Heravi, G.; Fathi, M.; Faeghi, S. Evaluation of sustainability indicators of industrial buildings focused on petrochemical projects. *J. Clean. Prod.* **2015**, *109*, 92–107. [CrossRef]
9. *A/RES/70/1 Transforming Our World: The 2030 Agenda for Sustainable Development*; United Nations: New York, NY, USA, 2015.
10. Ejsmont, K.; Gladysz, B.; Kluczek, A. Impact of Industry 4.0 on Sustainability—Bibliometric Literature Review. *Sustainability* **2020**, *12*, 5650. [CrossRef]
11. Zanni, M.; Soetanto, R.; Ruikar, K. Towards a BIM-enabled sustainable building design process: Roles, responsibilities, and requirements. *Archit. Eng. Des. Manag.* **2016**, *13*, 101–129. [CrossRef]
12. Boujaoude Khoury, K. Effective communication processes for building design, construction, and management. *Buildings* **2019**, *9*, 112. [CrossRef]
13. Kin, M.; Dawood, N.; Kassem, M. BIM for manufacturing: A case study demonstrating benefits and workflows and an approach for Enterprise Application Integration (EAI). In Proceedings of the 13th International Conference on Construction Applications of Virtual Reality, Hong Kong, 12–13 December 2016.
14. Näser, P.; Wickenhagen, N. Factory integration into building information modeling (BIM). In *wt Werkstattstechnik Online Jahrgang 108 (2018)*; Springer-VDI-Verlag GmbH & Co. KG: Düsseldorf, Germany, 2018; pp. 245–250.
15. Peukert, B.; Benecke, S.; Clavell, J.; Neugebauer, S.; Nissen, N.F.; Uhlmann, E.; Lang, K.-D.; Finkbeiner, M. Addressing sustainability and flexibility in manufacturing via smart modular machine tool frames to support sustainable value creation. *Procedia CIRP* **2015**, *29*, 514–519. [CrossRef]
16. Gosling, J.; Naim, M.; Sassi, P.; Iosif, L.; Lark, R. Flexible buildings for an adaptable and sustainable future. In Proceedings of the Association of Researchers in Construction Management (ARCOM) 24th Annual Conference, Cardiff, UK, 1–3 September 2008.
17. Cavalliere, C.; Dell'Osso, G.R.; Favia, F.; Lovicario, M. BIM-based assessment metrics for the functional flexibility of building designs. *Autom. Constr.* **2019**, *107*, 102925. [CrossRef]
18. Gourlis, G.; Kovacic, I. Building Information Modelling for analysis of energy efficient industrial buildings—A case study. *Renew. Sustain. Energy Rev.* **2017**, *68*, 953–963. [CrossRef]
19. Madson, K.M.; Franz, B.; Molenaar, K.R. Okudan Kremer Strategic development of flexible manufacturing facilities. *Eng. Constr. Archit. Manag.* **2020**, *27*, 1299–1314. [CrossRef]
20. Sahinidis, N.V.; Grossmann, I.E. Multiperiod investment model for processing networks with dedicated and flexible plants. *Ind. Eng. Chem. Res.* **1991**, *30*, 1165–1171. [CrossRef]
21. Flager, F. The Design of Building Structures for Improved Life-Cycle Performance. Master's Thesis, Massachusetts Institute of Technology, Cambridge, MA, USA, 2003.
22. Graubner, C. *Der Stadtbaustein im DAfStb/BMBF-Verbundforschungsvorhaben "Nachhaltig Bauen mit Beton"*; Deutscher Ausschuss für Stahlbeton e.V.-DafStb, Beuth: Berlin, Germany, 2014.
23. Slaughter, E.S. Design strategies to increase building flexibility. *Build. Res. Inf.* **2001**, *29*, 208–217. [CrossRef]
24. Rolvink, A.; Breider, J.; Coenders, J. Structural Components—A parametric associative design toolbox for conceptual structural design. In Proceedings of the International Association for Shell and Spatial Structures (IASS) Symposium. Evolution and Trends in Design, Analysis and Construction of Shell and Spatial Structures, Valencia, Spain, 28 September–2 October 2009; Universidad Politecnica de Valencia: Valencia, Spain, 2009.

5\. Mueller, C.T.; Ochsendorf, J.A. Combining structural performance and designer preferences in evolutionary design space exploration. *Autom. Constr.* **2015**, *52*, 70–82. [CrossRef]

6\. Di Giuda, G.M.; Giana, P.E.; Schievano, M.; Paleari, F. A collaborative approach for AEC industry digital transformation: A case study, the School of Liscate. In *Buildings for Education: A Multidisciplinary Overview of the Design of School Buildings*; Della Torre, S., Bocciarelli, M., Daglio, L., Neri, R., Eds.; Springer International Publishing: Cham, Germany, 2020; pp. 175–184. [CrossRef]

7\. Ebade Esfahani, M.; Burggräf, P.; Dannapfel, M.; Schneidermann, D.; Schwamborn, N. Integrated factory modelling: Using BIM to disrupt the interface between manufacturing and construction in factory planning. *WIT Trans. Built Environ.* **2019**, *192*, 143–155. [CrossRef]

28. Büscher, C.; Meisen, T.; Schilberg, D.; Jeschke, S. VPI-FP: An integrative information system for factory planning. *Int. J. Prod. Res.* **2016**, *54*, 2215–2226. [CrossRef]
29. Francalanza, E.; Borg, J.; Constantinescu, C. Development and evaluation of a knowledge-based decision-making approach for designing changeable manufacturing systems. *CIRP J. Manuf. Sci. Technol.* **2017**, *16*, 81–101. [CrossRef]
30. Mousavi, S.; Thiede, S.; Li, W.; Kara, S.; Herrmann, C. An integrated approach for improving energy efficiency of manufacturing process chains. *Int. J. Sustain. Eng.* **2016**, *9*, 11–24. [CrossRef]
31. Garwood, T.L.; Hughes, B.R.; Oates, M.R.; O'Connor, D.; Hughes, R. A review of energy simulation tools for the manufacturing sector. *Renew. Sustain. Energy Rev.* **2018**, *81*, 895–911. [CrossRef]
32. Deif, A.M. A system model for green manufacturing. *J. Clean. Prod.* **2011**, *19*, 1553–1559. [CrossRef]
33. Kluczek, A. An overall multi-criteria approach to sustainability assessment of manufacturing processes. *Procedia Manuf.* **2017**, *8*, 136–143. [CrossRef]
34. Kovacic, I.; Waltenbereger, L.; Gourlis, G. Tool for life cycle analysis of facade-systems for industrial buildings. *J. Clean. Prod.* **2016**, *130*, 260–272. [CrossRef]
35. Rodrigues, V.; Martins, A.A.; Nunes, M.I.; Quintas, A.; Mata, T.M.; Caetano, N.S. LCA of constructing an industrial building: Focus on embodied carbon and energy. *Energy Procedia* **2018**, *153*, 420–425. [CrossRef]
36. Tulevech, S.M.; Hage, D.J.; Jorgensen, S.K.; Guensler, C.L.; Himmler, R.; Gheewala, S.H. Life cycle assessment: A multi-scenario case study of a low-energy industrial building in Thailand. *Energy Build.* **2018**, *168*, 191–200. [CrossRef]
37. Bleicher, F.; Duer, F.; Leobner, I.; Kovacic, I.; Heinzl, B.; Kastner, W. Co-simulation environment for optimizing energy efficiency in production systems. *CIRP Ann.* **2014**, *63*, 441–444. [CrossRef]
38. Gourlis, G.; Kovacic, I. A study on building performance analysis for energy retrofit of existing industrial facilities. *Appl. Energy* **2016**, *184*, 1389–1399. [CrossRef]
39. Chen, D.; Heyer, S.; Seliger, G.; Kjellberg, T. Integrating sustainability within the factory planning process. *CIRP Ann.* **2012**, *61*, 463–466. [CrossRef]
40. Zhao, T.; Tseng, C.-L. Valuing flexibility in infrastructure expansion. *J. Infrastruct. Syst.* **2003**, *9*, 89–97. [CrossRef]
41. Geraedts, R. FLEX 4.0, a practical instrument to assess the adaptive capacity of buildings. *Energy Procedia* **2016**, *96*, 568–579. [CrossRef]
42. Cardin, M.-A.; Ranjbar-Bourani, M.; de Neufville, R. Improving the lifecycle performance of engineering projects with flexible strategies: Example of on-shore LNG production design. *Syst. Eng.* **2015**, *18*, 253–268. [CrossRef]
43. Marjaba, G.; Chidiac, S.E. Sustainability and resiliency metrics for buildings—Critical review. *Build. Environ.* **2016**, *101*, 116–125. [CrossRef]
44. Upton, D. What really makes factories flexible. *Harv. Bus. Rev.* **1995**, *73*, 74–85.
45. De Paris, S.R.; Lopes, C.N.L. Housing flexibility problem: Review of recent limitations and solutions. *Front. Archit. Res.* **2018**, *7*, 80–91. [CrossRef]
46. Cellucci, C.; Sivo, M. The flexible housing: Criteria and strategies for implementation of the flexibility. *J. Civ. Eng. Archit.* **2015**, *9*, 845–852. [CrossRef]
47. Živković, M.; Jovanović, G. A method for evaluating the degree of housing unit flexibility in multi-family housing. *Archit. Civ. Eng.* **2012**, *10*, 17–32. [CrossRef]
48. Glumac, B.; Islam, N. Housing preferences for adaptive re-use of office and industrial buildings: Demand side. *Sustain. Cities Soc.* **2020**, *62*, 102379. [CrossRef]
49. Israelsson, N. Factors influencing flexibility in buildings. *Struct. Surv.* **2009**, *27*, 138–147. [CrossRef]
50. Browne, J.; Dubois, D.; Rathmill, K.; Sethi, S.; Stecke, K. Classification of flexible manufacturing systems. *FMS Mag.* **1984**, *2*, 114–117.
51. Sethi, A.K.; Sethi, S.P. Flexibility in manufacturing: A survey. *Int. J. Flex. Manuf. Syst.* **1990**, *2*, 289–328. [CrossRef]
52. Wiendahl, H.P.; El Maraghy, H.A.; Nyhuis, P.; Zäh, M.F.; Wiendahl, H.H.; Duffie, N.; Brieke, M. Changeable manufacturing–Classification, design and operation. *CIRP Ann.* **2007**, *56*, 783–809. [CrossRef]
53. Moline, A. Recipe for Change: The Flexible Food Processing Plant of the Future. In DesignFlex2030, Industrial Asset Management Council (IAMC) and SIOR, GA, USA. 2015. Available online: https://www.sior.com/docs/default-source/default-document-library/DesignFlex2030.pdf (accessed on 17 September 2021).
54. Moline, A. Rx for change: The Flexible Biopharma Facility of the Future, In DesignFlex2030, Industrial Asset Management Council (IAMC) and SIOR, GA, USA. 2017. Available online: https://www.sior.com/docs/default-source/white-papers/dflex2030---rx-for-change.pdf?sfvrsn=0 (accessed on 17 September 2021).
5. Cardin, M.-A. Enabling flexibility in engineering systems: A taxonomy of procedures and a design framework. *J. Mech. Des.* **2014**, *136*, 011005. [CrossRef]
6. Shen, L.; Tam, V.; Yao, H. A checklist for assessing sustainability performance of construction projects. *J. Civ. Eng. Manag.* **2007**, *13*, 273–281. [CrossRef]
7. Shen, L.; Asce, M.; Wu, Y.; Zhang, X. Key assessment indicators for the sustainability of infrastructure projects. *J. Constr. Eng. Manag.* **2011**, *137*, 441–451. [CrossRef]
8. San-José Lombera, J.-T.; Garrucho Aprea, I. A system approach to the environmental analysis of industrial buildings. *Build. Environ.* **2010**, *45*, 673–683. [CrossRef]

59. Heravi, G.; Fathi, M.; Faeghi, S. Multi-criteria group decision-making method for optimal selection of sustainable industrial building options focused on petrochemical projects. *J. Clean. Prod.* **2017**, *142*, 2999–3013. [CrossRef]
60. Nadoushani, Z.; Akbarnezhad, A. Effects of structural system on the life cycle carbon footprint of buildings. *Energy Build.* **2015**, *102*, 337–346. [CrossRef]
61. Lee, B.; Pourmousavian, N.; Hensen, J.L.M. Full-factorial design space exploration approach for multi-criteria decision making of the design of industrial halls. *Energy Build.* **2016**, *117*, 352–361. [CrossRef]
62. Vardopoulos, I. Critical sustainable development factors in the adaptive reuse of urban industrial buildings. A fuzzy DEMATEL approach. *Sustain. Cities Soc.* **2019**, *50*, 101684. [CrossRef]
63. Wiendahl, P.; Reichardt, J.; Nyhuis, P. *Handbook Factory Planning and Design*; Springer: Berlin/Heidelberg, Germany, 2015; Volume 1. [CrossRef]
64. Woodhead, R.; Stephenson, P.; Morrey, D. Digital construction: From point solutions to IoT ecosystem. *Autom. Constr.* **2018**, *93*, 35–46. [CrossRef]
65. Grilo, A.; Jardim-Goncalves, R. Value proposition on interoperability of BIM and collaborative working environments. *Autom. Constr.* **2010**, *19*, 522–530. [CrossRef]
66. Sibenik, G.; Kovacic, I. Assessment of model-based data exchange between architectural design and structural analysis. *J. Build. Eng.* **2020**, *32*, 101589. [CrossRef]
67. Succar, B. Building information modelling framework: A research and delivery foundation for industry stakeholders. *Autom. Constr.* **2009**, *18*, 357–375. [CrossRef]
68. Zhang, X.; Azhar, S.; Nadeem, A.; Khalfan, M. Using building information modelling to achieve lean principles by improving efficiency of work teams. *Int. J. Constr. Manag.* **2018**, *18*, 300. [CrossRef]
69. Rahmani Asl, M.; Zarrinmehr, S.; Bergin, M.; Yan, W. BPOpt: A framework for BIM-based performance optimization. *Energy Build.* **2015**, *108*, 401–412. [CrossRef]
70. Schuh, G.; Kampker, A.; Wesch-Potente, C. Condition based factory planning. *Prod. Eng.* **2011**, *5*, 89–94. [CrossRef]
71. Bejjani, C.; Utsch, J.; Thiele, T.; Meisen, T.; Jeschke, J.; Burggräf, P. Flow Chart based information modeling for factory planning. *Procedia CIRP* **2018**, *72*, 410–415. [CrossRef]
72. Hawer, S.; Sager, B.; Braun, H.; Reinhart, G. An adaptable model for the factory planning process: Analyzing data based interdependencies. *Procedia CIRP* **2017**, *62*, 117–122. [CrossRef]
73. Kampker, A.; Mecklenborg, A.; Burggräf, P.; Netz, T. Factory planning scrum: Integrative factory planning with agile project management. In Proceedings of the International Conference on Competitive Manufacturing (COMA '13), Stellenbosch, South Africa, 30 January–1 February 2013.
74. Graefenstein, J.; Winkels, J.; Lenz, L.; Weist, K.C.; Krebil, K.; Gralla, M. A hybrid approach of modular planning—Synchronizing factory and building planning by using component based synthesis. In Proceedings of the 53rd Hawaii International Conference on System Sciences, Wailea, HI, USA, 7–10 January 2020.
75. Lenz, L.T.; Gralla, M.; Höpfner, M.; Spyridis, P.; Weist, K.C. BIM approach for decision support: Case study fastening systems in factory adaptation planning. In Proceedings of the 2019 European Conference on Computing in Construction, Chania, Greece, 10–12 July 2019; pp. 2–8. [CrossRef]
76. Delbrügger, T.; Lenz, L.T.; Losch, D.; Roßmann, J. A navigation framework for digital twins of factories based on building information modeling. In Proceedings of the 22nd IEEE International Conference on Emerging Technologies and Factory Automation (ETFA), Limassol, Cyprus, 12–15 September 2017. [CrossRef]
77. The design process—Early stages. In *The ASHRAE GreenGuide*, 2nd ed.; Butterworth-Heinemann: Burlington, MA, USA, 2006; pp. 73–100.
78. Sadafi, N.; Mohd Zain, M.F.; Jamil, M. Design criteria for increasing building flexibility: Dynamics and prospects. *Environ. Eng. Manag. J.* **2014**, *13*, 407–417. [CrossRef]
79. Lee, J.H.; Ostwald, M.J. Creative decision-making processes in parametric design. *Buildings* **2020**, *10*, 242. [CrossRef]
80. Büscher, C.; Voet, H.; Meisen, T.; Krunke, M.; Kreisköther, K.; Kampker, A.; Schilberg, D.; Jeschke, S. Improving factory planning by analyzing process dependencies. *Procedia CIRP* **2014**, *17*, 38–43. [CrossRef]
81. Cuadrado, J.; Zubizarreta, M.; Roji, M.; García, H.; Larrauri, M. Sustainability-related decision making in industrial buildings: An AHP analysis. *Math. Probl. Eng.* **2015**, *2015*, 157129. [CrossRef]
82. Chinese, D.; Nardin, G.; Saro, O. Multi-criteria analysis for the selection of space heating systems in an industrial building. *Energy* **2011**, *36*, 556–565. [CrossRef]
3. Albers, S.; Klapper, D.; Konradt, U.; Walter, A.; Wolf, J. *Methodik der Empirischen Forschung*; Gabler Verlag: Wiesbaden, Germany, 2009. [CrossRef]
4. Bogner, A.; Littig, B.; Menz, W. *Interviews mit Experten. Eine Praxisorientierte Einführung*; Springer: Berlin/Heidelberg, Germany, 2014; Volume 1. [CrossRef]
5. Radson, D.; Boyd, A.H. The pareto principle and rate analysis. *Qual. Eng.* **1997**, *10*, 223–229. [CrossRef]
6. Kovacic, I.; Müller, C. Challenges for the implementation of integrated design in the planning practice. *Procedia—Soc. Behav. Sci.* **2014**, *119*, 529–538. [CrossRef]

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RESEARCH ARTICLE

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

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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

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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

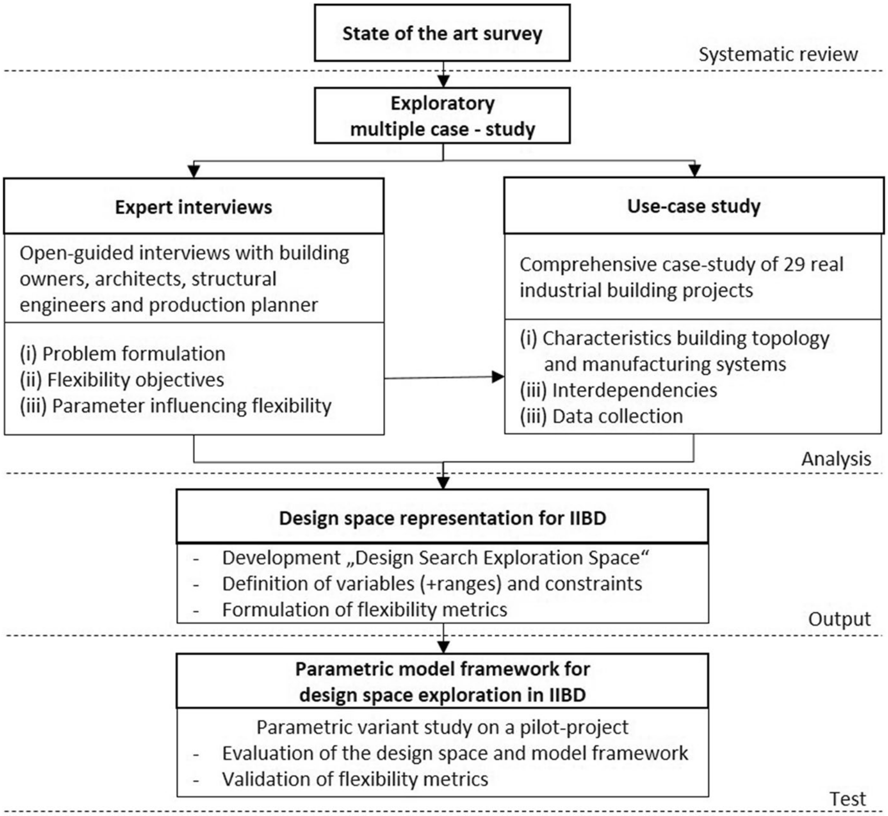

Fig. 1 Overview of the research methodology and scope of paper

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 *variable* or outcome and must be satisfied for an *alternative* to be valid
Metrics	The definition of *metrics* allows the verification of the fulfillment of the *constraints* 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 *alternative* corresponds to a particular set of options for every variable of the problem
Variables	can be discreet or continuous input parameter within a *range* that constrain all possible states of such a *variable* 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.

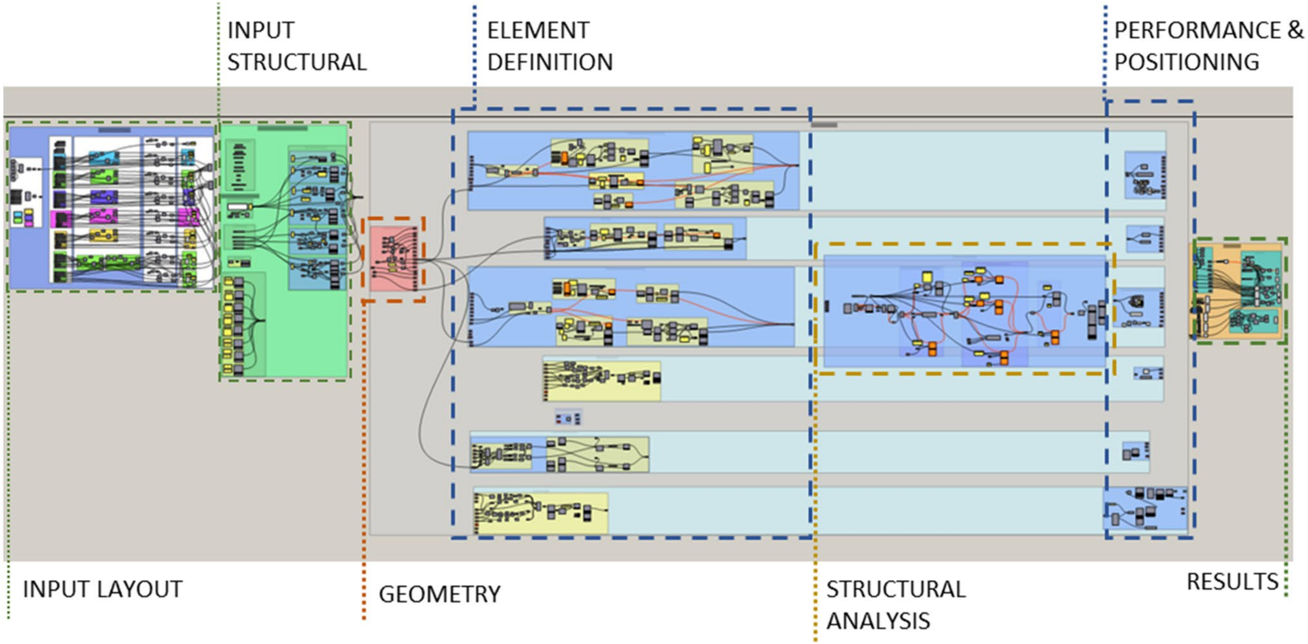

Fig. 2 The developed parametric model framework in Grasshopper for Rhino3D. To test the feasibility of the design space and to validate the flexibility metrics a variant study on a pilot use case from the food-and hygiene production sector is conducted at the end of the study

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: $H\{\boldsymbol{f}_i, \boldsymbol{g}_j, \boldsymbol{h}_k, r_i, s_j, t_{i,j}\}$. Here, $\mathbf{f}_i$, $\mathbf{g}_j$, $\mathbf{h}_\mathrm{k}$ 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 $t_{i,j}$ 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 ($t_{i,j}$ = 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: $\boldsymbol{f}_i, \boldsymbol{g}_j, \boldsymbol{h}_k, r_i, s_j, t_{i,j}$. 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).

$$\mathrm{f}_i \geq 0, i \in \{1, 2, \ldots, N_f\} \tag{1}$$

$$\mathrm{g}_j \geq 0, j \in \{1, 2, \ldots, N_g\} \tag{2}$$

$$\mathrm{h}_k \geq 0, k = 1 \tag{3}$$

$$A_R = \sum_{i=1}^{Nf} \sum_{j=1}^{Ng} a_{i,j} = \sum_{i=1}^{Nf} \sum_{j=1}^{Ng} \left| \vec{f_i} \times \vec{g_j} \right| \tag{4}$$

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,)

$t_{i,j}$ = (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

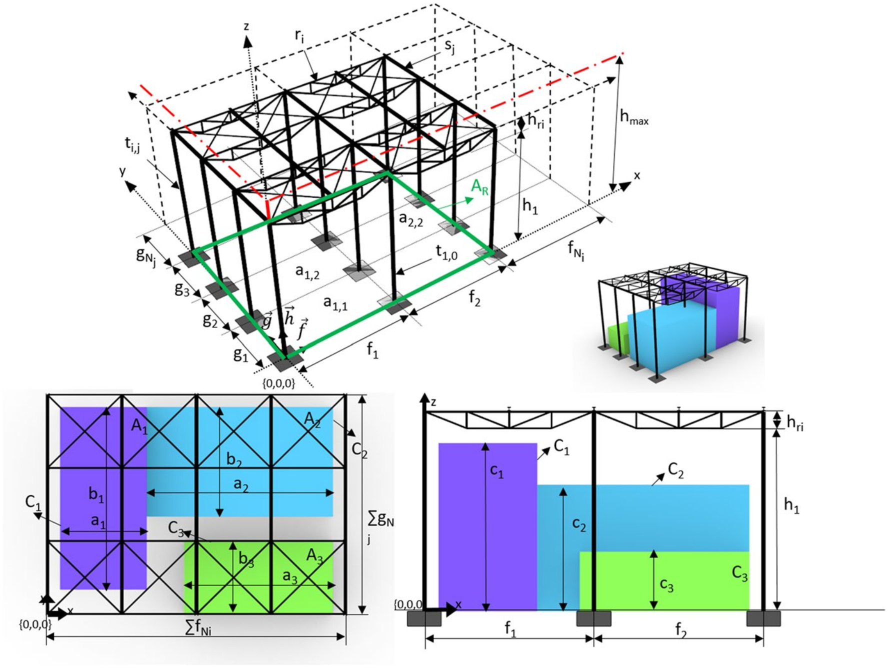

Fig. 3 The industrial building is described by grid vectors $\mathbf{f}_i$, $\mathbf{g}_j$, $\mathbf{h}_k$ and grid element variables r_i, s_j, $t_{i,j}$, while the production layout contains production cubes C_p described by the variables a_p, b_p, c_p

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:

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

$$A_p = \sum_{p=1}^{m} areaofR_p = \sum_{p=1}^{m} (a_p \cdot b_p) \tag{6}$$

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_i, g_j, 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_i, 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/m^2 (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. $X = \left\{x_1, x_2, \ldots, x_n\right\}$: 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})

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

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

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

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

$$\delta_{ri,sj} \leq \delta_a = l/300 \tag{10}$$

Constraint x_3: stability of $H\left\{\boldsymbol{f}_i, \boldsymbol{g}_j, \boldsymbol{h}_k, r_i, s_j, t_{i,j}\right\}$ 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	7
g_j	Secondary Axis Grid (y-)	continuous/ constrained	Input/ user modifiable	m	6	24	4
N_f	Primary Axis fields	continuous/ constrained	Input/ user modifiable	pc	1	8	8
N_g	Secondary Axis fields	continuous/ constrained	Input/ user modifiable	pc	1	14	14
h_k	Inner Hall Height (z-)	Continuous	Input/ user modifiable	m	$h_k <=$ maximum. building height—construction height		
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							
$t_{i,j}$	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 Rp is described as the sum of all production cubes Cp

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}:

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

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

$$\mathring{R}_q \cap \mathring{R}_r = \emptyset \text{ for } q \neq r \text{ and } q, r = \{1, 2, \ldots, m\} \tag{13}$$

where $\mathring{R}$ 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:

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

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 ≤ 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 ≤ 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]

$$R \subseteq R_{Prop} \tag{15}$$

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

$$€_{max} \cdot 1.30 \leq €_H \tag{16}$$

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.

$$\mathrm{RF} = \frac{F_{RT}}{F_{RT,max}} \tag{17}$$

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 inversed 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:

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

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}- $c_{p,max}$).

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

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.

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

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 m^2. 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

Flexibility assessment metrics in IIBD

	Key Indicator	Goal	Performance Indicator	Scenario/ Parameter	Metric	Evaluation Method
O4	Retrofittability	Maximum Structural capacity	Retrofitting Load RF	Retrofitting Load	% (N/mm^2)	F_{RT}-ratio
O5	Expandability	Expandability of production	Floor space reserve A_{FS}	Unused Floor Area	% (m^2)	PERC-based
O6	Flexibility in space	Maximum Hall height reserve	Height reserve Hr	Unused height	% (m)	DIST-based
O7	Flexibility in floor plan	No columns inside hall	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/m^2. 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/m^2 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/m^2 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/m^2 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

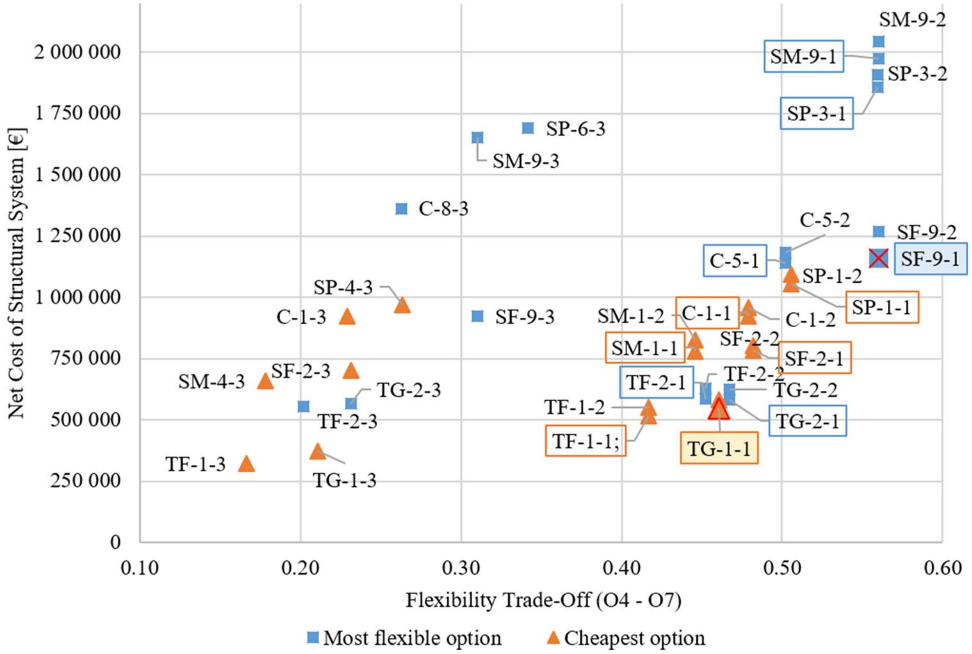

Fig. 4 shows the most flexible and lowest cost alternatives examined in the design space

Table 9 Representation of the most flexible alternatives, when the hall dimensions are 120 m × 48 m, the retrofitting load = 1.0 kN/m^2 and bracing type = 0 and the variant by increased hall size

Most flexible alternatives (Ar = 120 m × 48 m = 5 760 m^2, F_{RF} = 1.0 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
O5 Increased hall Size						
Ar = 140 m • 48 m = 6 720 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, retrofitting load = 1.0 kN/m^2 and bracing type = 0 and a variant, with no retrofitting load

Lowest cost alternatives (Ar = 120 m × 48 m = 5 760 m^2 and F_{RF} = 1.0 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
O4—Variant no retrofitting						
F_{RF} = 0.00 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.

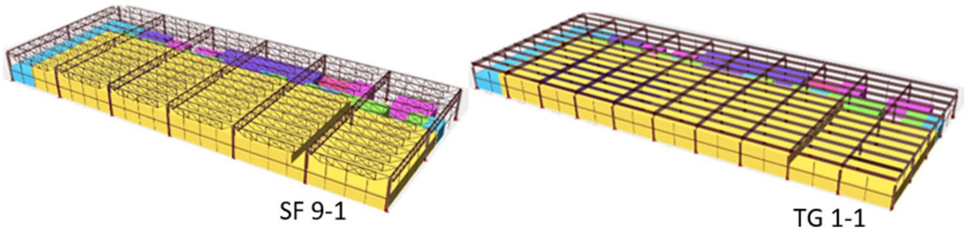

Fig. 5 Visualization of the most flexible alternative (steel framework SF-9–1) and the lowest cost alternative (timber girder TG-1–1) in Rhino3D

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

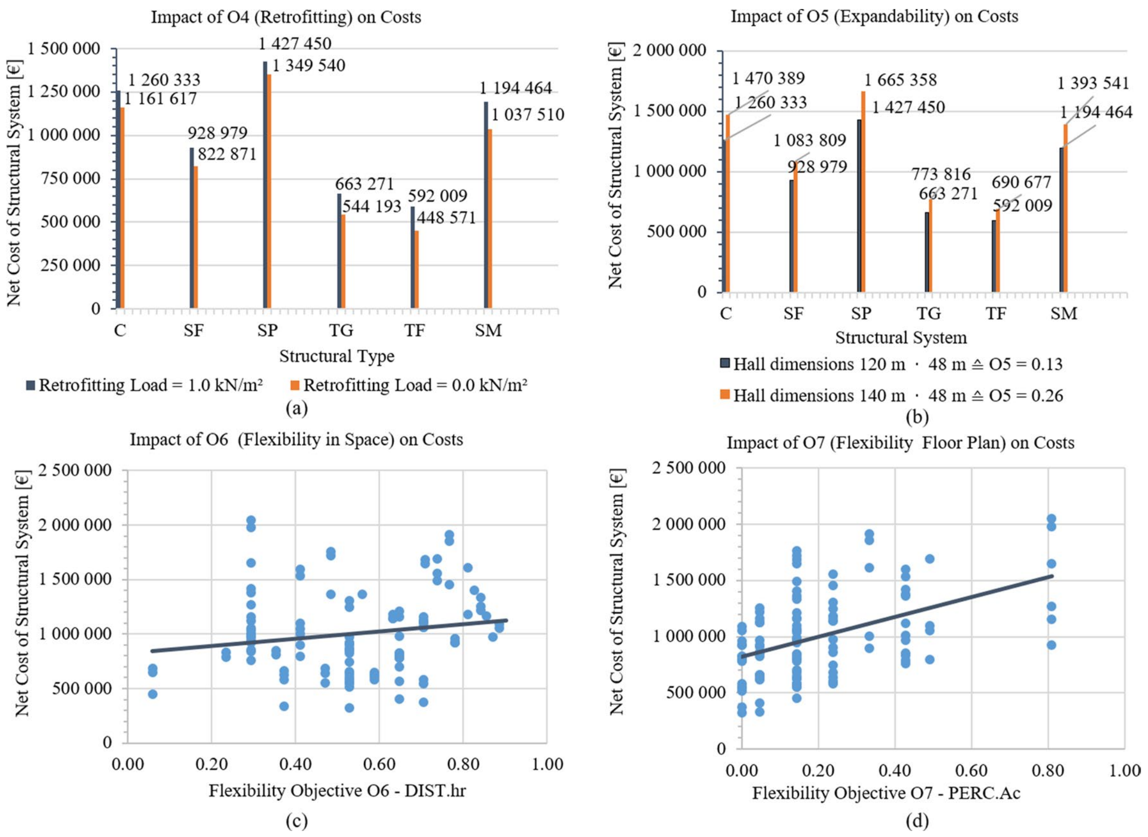

Fig. 6 Impact analysis of the flexibility objectives on the costs of the structure: **a** cost impact of O4, the retrofitting ability; **b** cost impact of O5, the expandability; **c** cost impact of O6, the flexibility in space and **d** cost impact of O7, the flexibility of the floor plan

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.

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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

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, Szwejczewski 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, Waltenbereger 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://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

Sóbester A, Powell S (2013) Design space dimensionality reduction through physics-based geometry re-parameterization. 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, Brieke 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

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Julia Reisinger, Maria Antonia Zahlbruckner, Iva Kovacic, Peter Kán,
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“Integrated multi-objective evolutionary optimization of production layout scenarios for parametric structural design of flexible industrial buildings.”

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Integrated multi-objective evolutionary optimization of production layout scenarios for parametric structural design of flexible industrial buildings

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ABSTRACT

Due to product individualization, customization and rapid technological advances in manufacturing, production systems are faced with frequent reconfiguration and expansion. Industrial buildings that allow changing production scenarios require flexible load-bearing structures and a coherent planning of the production layout and building systems. Yet, current production planning and structural building design are mostly sequential and the data and models lack interoperability. In this paper, a novel parametric evolutionary design method for automated production layout generation and optimization (PLGO) is presented, producing layout scenarios to be respected in structural building design. Results of a state-of-the-art analysis and a case study are combined to develop a novel concept of integrated production cubes and the design space for PLGO as basis for a parametric production layout design method. The integrated production cubes concept is then translated into a parametric PLGO framework, which is tested on a pilot-project of a hygiene production facility to evaluate the framework and validate the defined constraints and objectives. Results suggest that our framework can produce feasible production layout scenarios, which respect flexibility and building requirements. In future research the design process will be extended by the development of a multi-objective evolutionary optimization process for industrial buildings to provide flexible building solutions that can accommodate a selection of several prioritized production layouts.

1. Introduction

Industry 4.0 describes the trend towards increased digitization and automation of manufacturing systems [1] and targets the realization of production in batch size of one and individualization on demand within short periods [2]. Constant reconfiguration and expansion of manufacturing systems demand highly flexible industrial buildings. The load-bearing structure is recognized as the most rigid element with the longest service life in a building [3] and restricts the adaptability and transformability of production layouts. The economic life cycle of classical building typologies ranges from 50 to 80 years, while industrial buildings are characterized by

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very short life cycles ranging from 15 to 30 years. The extension of industrial buildings service life could increase the economic and environmental performance of production facilities, nonetheless, flexible production systems bear challenges on the structural building design [4]. Hence, industrial buildings should strive for maximum flexible load-bearing structures, allowing rapid adjustments and simple reconfiguration of production layouts. Consequently, the focus in industrial building design needs to be on a coherent planning of the production layout and the structural building systems.

An integrated design approach, in which all systems and components work together, is one of the most important aspects for well-designed, cost-effective buildings to improve the overall functionality and environmental performance. To have a direct impact on building performance requires to develop design alternatives that are evaluated, refined, and optimized already early in the design process, i.e. during the program and schematic design phases [5]. Production facilities, referring to a building or area where products are made, and production systems, referring to the methods used in industry to create products from various resources, are generally heavy, fixed, and normally irreversible once construction has been completed [6]. By including flexibility early in the design process, the lifetime investment in production facilities that experience change can be reduced [7]. Currently building and production planning processes are sequential and neglect discipline-specific interactions [8]. Integrated factory modelling is complex as models, data and processes lack in interoperability and are held in discipline-specific silo thinking [9]. As a result, a lack of methods exists which integrate production layout planning and structural building design, coherently optimizing both systems.

The automated solving of the layout problem in production planning represents one of the most essential processing steps in factory planning and is linked to many other components within production facilities. Current production layout planning methods are mainly conducted manually and are based on assignment activities [10]. Determining the physical organization of a production system can be defined as facility layout problem (FLP) [11] that focuses on allocating the facilities that make up an industrial plant in the best possible way [12] under several optimization criteria and different constraints [13]. Although additional criteria or aspects could be considered in FLP to enrich the quality of design solutions [14] the most common objective in FLP is the minimization of the material handling costs between the facilities [15,16]. One of the most promising methods for automated production layout generation and optimization is a multi-objective evolutionary algorithm approach [13,17,18]. To find high performing designs, the concrete mathematical formalization of the design space and objectives by which each scenario can be evaluated is required as basis for optimization [19]. There is a lack of multi-objective production layout optimization methods incorporating flexibility and building related criteria and restrictions.

Parametric and performance-based design tools offer design teams both, an efficient method to explore broad design spaces with rapid feedback for well-informed decision-making [20] and a possibility to integrate multiple design disciplines for multi-objective optimization [21]. Various research is conducted on parametric design and optimization of building structures [22,23]. More work is needed to explore parametric production layout optimization methods. A parametric design procedure for automated generation and optimization of production layout scenarios for integration into structural building design processes has already been presented by the authors in Reisinger et al. [24]. The mentioned paper presents the design space definition and the development of our parametric production layout generation and optimization (PLGO) framework.

This paper presents ongoing research conducted within the funded research project BIMFlexi, which aims to develop a holistic digital platform for design and optimization of industrial buildings towards maximum flexibility by integrating building and production processes and models [25]. The aim of the presented research is the design space development for parametric PLGO, which is based on a novel concept of integrated production cubes [24]. The developed evolutionary algorithm integrates flexibility and building criteria and enables automated multi-objective optimization of production layout scenarios with quantitative objective assessment and layout visualization for multidisciplinary decision-making support. The focus of this paper is to provide a comprehensive overview and evaluation of our PLGO framework and the separate analysis of constraints and objectives on a more suitable test case from industry incorporating feedback from experts using the framework. The main research questions investigated in this research are:

1.) What are the design variables, constraints and objectives for automated production layout planning, integrating flexibility and building criteria, and how can they be mathematically formulated for a multi-objective evolutionary algorithm?
2.) What are the requirements and necessary structure of a parametric framework for PLGO, which can be integrated into structural building design processes to maximize the flexibility and expandability of production facilities in long-term?

The paper is structured as follows: first, the state of the art on flexibility, integrated industrial building design optimization, space layout and production layout generation and integration possibilities through parametric design through literature review is presented. Second, the developed methodology is described. Based on the results, a novel integrated production cubes concept and the PLGO framework is presented. The PLGO framework is tested and evaluated and the defined objectives and constraints validated on a pilot-case. Finally, the results and future steps are discussed.

2. Literature review

The main aim of this research is to create a methodology to optimize the structure of production facilities that allows future adaptations of production systems without complete rescheduling or demolition of the building structures. Production systems can be called flexible when they can be easily accommodated to dynamic market requirements [26]. A robust production facility must be able to accommodate a range of products, moving the facility from a specific product to a more generalized group of products. Flexibility is not a one-size-fits-all approach and can be rather cultivated at varying levels by a series of design choices [27]. Various research define flexibility concepts and metrics for residential buildings [28–30], the adaptive capacity of buildings [31], or the adaptive re-use of office and industrial buildings [32]. Browne et al. [33] and Sethi and Sethi [34] define the most common production flexibility dimensions as machine flexibility, operation flexibility, routing flexibility, volume flexibility, expansion flexibility, process flexibility, product flexibility, production flexibility, material handling flexibility, programme flexibility and market flexibility. Wiendahl et al. [35] describe five transformation enablers of production facilities as Universality, Scalability, Modularity, Mobility and Compatibility. Some studies consider the flexible design of a specific production type, such as food processing facilities [36] and pharmaceutical facilities [37]. Madson et al. [27] address the lack of formal design guidance that supports flexibility within architectural and engineering systems of production facilities. However, no conventional flexibility definition for production layout planning, taking into account building criteria, has been established. A reason could be that in production planning the term flexibility is not uniform as managers face three main issues: flexibility is not easy to measure; the products that a plant produces do not necessarily reflect its flexibility and it is often unclear which features of a plant must be changed in order to make its operations flexible [38]. In Reisinger et al. [39] we presented a design guideline for flexible industrial buildings integrating Industry 4.0 requirements. The study results revealed that for the successful design of flexible industrial building structures, novel powerful computational models for multi-objective design optimization and interdisciplinary decision-making support are required, integrating production planning parameters such as machine types, machine sizes and production planning layouts into building design.

Optimization is a field of applied mathematics and computer science in which modelling and algorithms are used to find the best solutions to complex problems. In particular, problems are considered in which a large number of unknown parameters are used. Multi-objective optimization can help to assist in handling with multiple conflicting criteria and support in decision making. In literature, research on production layout planning and optimization to be integrated in industrial building design processes is rare. Research has been conducted on optimization of product or manufacturing processes [40–43]. Among the conducted research on industrial building level, several authors proposed optimization models that focus on the buildings energy performance [44–46], the selection of the best HVAC system [47] or on the integration of building and active energy systems [48]. While building materials from load-bearing structure and enclosure systems are the main responsible for the total embodied energy and carbon in industrial buildings [49], integrated optimization models, coherently respecting production planning and structural building design receive little attention. Indeed, the focus in early industrial building design should be on the optimization of the load-bearing structure, simultaneously considering different production layout scenarios allocated in space.

Layout problems arise in different areas of applications and hence encompass several classes of optimization problems. The facility layout problem is an optimization problem that arises in a variety of scenarios such as placing machines on a factory floor. The common objective is to reduce material handling costs between the facilities [15,16]. Numerous computational methods have been developed for automation of spatial layout problems and multi-objective optimization for process plan generation and facility layout problems, but objectives and scope of these programs vary widely. Automated space allocation algorithms require specific evaluation methods to guide the layout process properly. There are three major solution techniques for automated layout generation in buildings: (1) the optimization of a single criterion function, (2) the graph theoretic approach, (3) and multi-objective optimization, finding an arrangement that satisfies a diverse set of constraints (position, orientation, adjacency, path, distance) [50]. Various research dealt with an automated generation of architectural floorplans or space layout planning [51–55], mostly utilizing evolutionary algorithms. Dorrah and Marzouk [56] presented an integrated multi-objective optimization and agent-based building occupancy modelling for space layout planning. Bilal et al. [57] proposed a convex optimization-based algorithm for finding alternative building floor layouts to enforce the design for dimensional coordination and to reduce construction waste. Claessens et al. [58] presented a three-dimensional spatial zoning procedure that has been tailored to structural design, using grammars. Boonstra et al. [59] developed two methods to generate structural system layouts for conceptual building spatial designs, first a response grammar and second an evolutionary algorithm to assign structural components to a building spatial design geometry. Above-mentioned research focused primarily on architectural layout and space allocation of residential or office buildings. More research work is needed on floorplan and space layout planning for industrial building design. Despite increasing digitization and extensive computational support in production layout planning, the process of a new design generation including the production logistic aspects still requires manual handling, making it an unpleasant task [10]. Different methods and algorithms in production planning can be used to develop new layouts such as Systematic Layout Planning, Pairwise Exchange Method, Graph Based Theory, Dimensionless Block Diagram or Total Closeness Rating [60]. The facility layout problem (FLP) is an optimization problem, which arises in a variety of problems such as placing machines on a factory floor. The output of the FLP is a block layout that specifies the relative location of each department. In most cases, the main objective in facility layout problems is to minimize material handling costs [15,16]. The layout problem is an operations research problem of finding the optimal arrangement for a number of non-overlapping indivisible departments within a given facility [61]. The FLP is particularly relevant in flexible manufacturing systems that produce an array of different parts. The material handling cost is determined based on the flows of materials between departments and the distances between the locations of the departments [62]. Several evolutionary algorithm methods have been proposed for layout planning and optimization [10,63,64]. Evolutionary computation research with multi-objective interactive genetic algorithms are used to solve optimization process based on distance requirements, adjacency requests and aspect ratio constraints [17] and decision-making preferences for facility layout design [65]. Palomo-Romero et al. [16] presented an island model genetic algorithm for unequal area facility problems, stating that interactive algorithms often execute slowly because they require the intervention of a human expert and the decision maker can be at risk of fatigue due to the amount of information to be evaluated. Garcia-Hernandez et al. [13] address unequal area facility layout problems with the coral reef optimization algorithm. Aiello et al. [14] used a multi-objective genetic algorithm to evolve the population, ranking according to a set of criteria given by the decision makers. Chae and Regan [66] dealt with a FLP model that minimizes the material handling cost between rectangular departments. Each department has an area restriction that specifies the total area that it must occupy while the specific lengths and widths are determined by the model. Wang et al. [67] proposed a systematic approach of process planning and scheduling optimization for sustainable machining of shop floors using artificial neural networks. Touzout and Benyoucef [68] addressed the multi-objective single product-multi-unit process plan generation problem in a reconfigurable manufacturing environment, proposing three hybrid heuristics. The single-unit process plans are generated using a genetic algorithm. In addition to the classical total production cost and the total completion time, the authors minimize the maximum machines exploitation time. Li et al. [69] focused on the dynamic facility layout of the manufacturing unit considering human factors and build a mathematic model to find the best solution combining safety, sustainability, high efficiency, and low cost. Khezri et al. [70] addressed an environmental oriented multi-objective optimization problem for a sustainable process plan generation in a reconfigurable manufacturing context. The problem considers three criteria to minimize respectively the sustainability-metric value, the total production time and the total production cost. Shabaka and ElMaraghy [15] presented a model for optimizing the manufacturing cost of process plans for reconfigurable manufacturing systems using genetic algorithms. El-Baz [71] described a genetic algorithm to solve the problem of optimal facility layouts in manufacturing systems, minimizing the material handling costs. The authors considered various material flow patterns of manufacturing environments such as flow shop layout, single line layout with multi-products, multi-line layout, semi-circular layout and loop layout. Gonçalves and Resende [72] presented a biased random key genetic algorithm for the unequal area facility layout problem where a set of rectangular facilities with given area requirements have to be placed, without overlapping, on a rectangular floor space. The objective was to find the location and the dimensions of the facilities such that the sum of the weighted distances between the centroids of the facilities is minimized. Shoja Sangchooli and Akbari Jokar [73] introduced a technique for accruing an initial placement of facilities on an extended plane, obtained by graph theoretic facility layout approaches and graph drawing algorithms. The mathematical optimization models generally used have been subject to 18 different types of constraints, of which the most widely used in FLP are: Area restrictions; non overlapping between departments; number of material handling devices; budget; capacity; pick up/drop off point locations; departments orientation and the clearance between departments. Moreover, most optimization models consider a single quantitative objective function that simultaneously involves material handling costs and rearrangement costs. Qualitative factors like closeness ratings among departments, layout flexibility or safety issues may be more relevant to some industries but are often not included [74]. The above research is remarkable, nevertheless, there is a dearth of research works that investigate production layout generation and optimization for model integration directly into industrial building design processes. Either researches are optimizing space layouts in architectural design or facility layouts of production systems, a mutual consideration was not observed.

Parametric design and performance-based tools offer a great opportunity to integrate discipline-specific systems. Designers get quick feedback about how different alternatives behave and get guidance for decision-making [22]. Parametric design supports exploration and design search and allows efficient navigation through the design space [75]. Parametric and performance-based design tools have been widely employed by researchers and practitioners in architectural and structural design domain [22,76–79]. Nourian et al. [80] develop a parametric design methodology for configurative design of architectural plan layouts. A parametric design process shows remarkable potential for, enabling the integration into structural building design processes. Thus, to achieve integration several production, architectural, structural and technical service system aspects and their interdependencies need to be considered. In Reisinger et al. [24] we offered a parametric framework for automated generation of production layout scenarios on the specificities of integrated industrial building design. This new paper presented here is part of the previous research and provides a new comprehensive evaluation and more detailed explanation of our framework.

Based on the literature presented on flexible production facilities, integrated industrial building optimization, space layout and facility layout problems and parametric design for optimization and integration there remain some research gaps for facility layout generations. Despite the impact of changing facility layouts on the building performance and its service life, the majority of studies on facility layout problems focus on the optimization of material handling cost. Therefore, more studies are needed on the incorporation of building related requirements in facility layout planning, especially from structural design for prolonged building service life. Second, with the increasing potential of parametric and performance-based design tools for coupling of discipline-specific systems for multi-objective optimization of building designs, it is imperative to investigate opportunities for the integration of facility layout planning directly into the building design process. This will facilitate the realization of more flexible and sustainable industrial buildings and enable early variant studies and multidisciplinary decision support. Third, previous research on layout planning in building design has mainly been conducted for office and residential buildings, without considering industrial buildings that experience changing spaces with different requirements for production operations. Finally, there is a need to develop a parametric design approach that incorporates multi-objective optimization of production layouts considering building design criteria and flexibility metrics, which is the aim of this paper.

3. Research design

The purpose of our presented research is the development of the design space (variables, constraints and objectives) and the parametric framework for automated PLGO respecting both, production and building requirements with the focus on flexibility. Fig. 1 gives an overview of the research design, the outputs and the future steps.

The research methodology is based on an exploratory multiple case study [81], using the sources of expert interviews and a use-case study of documents and archival records, the development of a multi-objective evolutionary algorithm and parametric modeling. For the case study, 28 real industrial building projects, representative for the research objective, served as use-cases [82]. Different production types were examined (automotive, food and hygiene, logistic, metal processing and special products) to create a diversity and to not exclusively investigating the requirements of a specific production sector. Within the case study, documentations, archival records and digital models were investigated to collect data from manufacturing system requirements and production layout

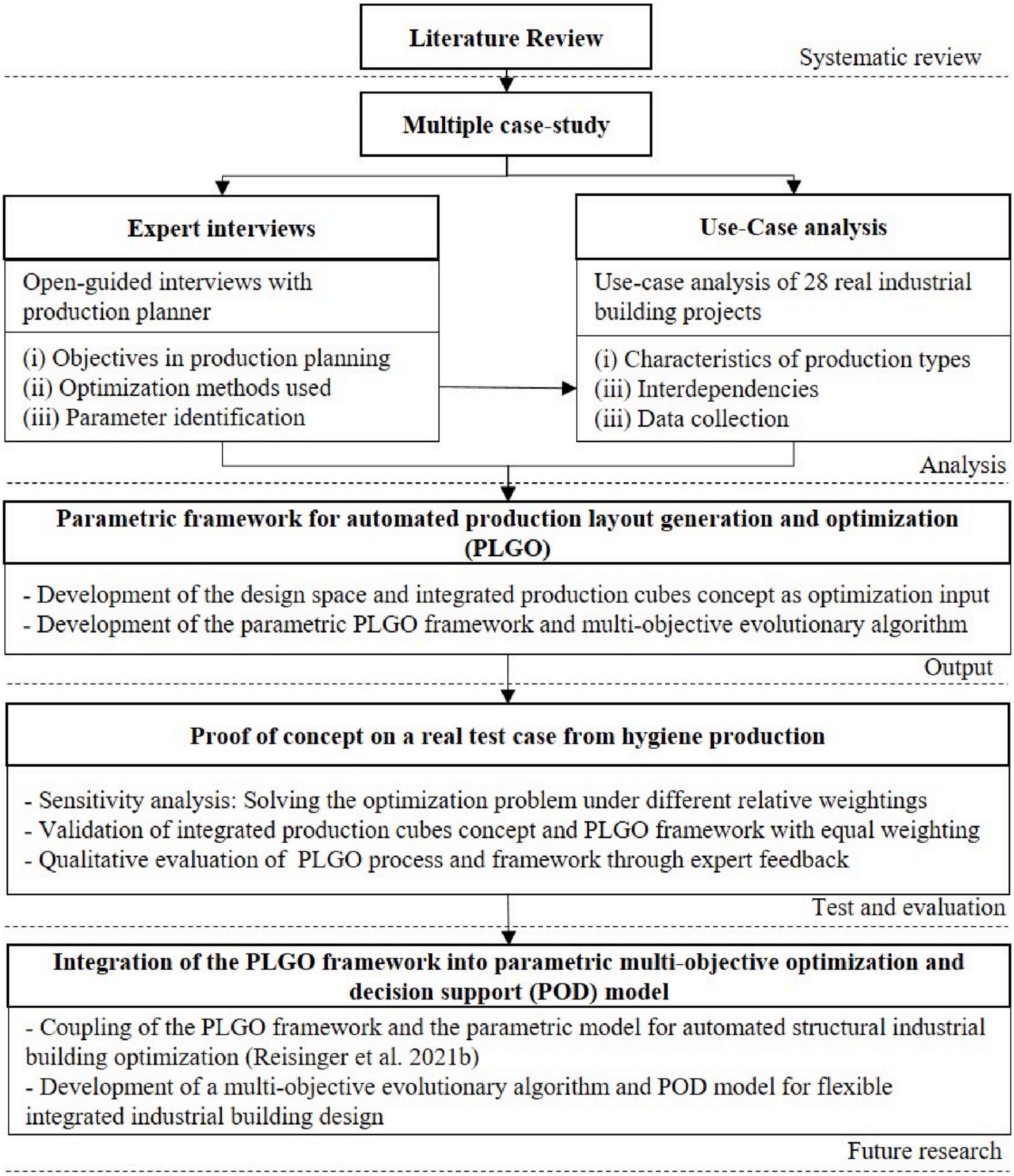


Fig. 1. Overview of the research design and the scope of the paper.

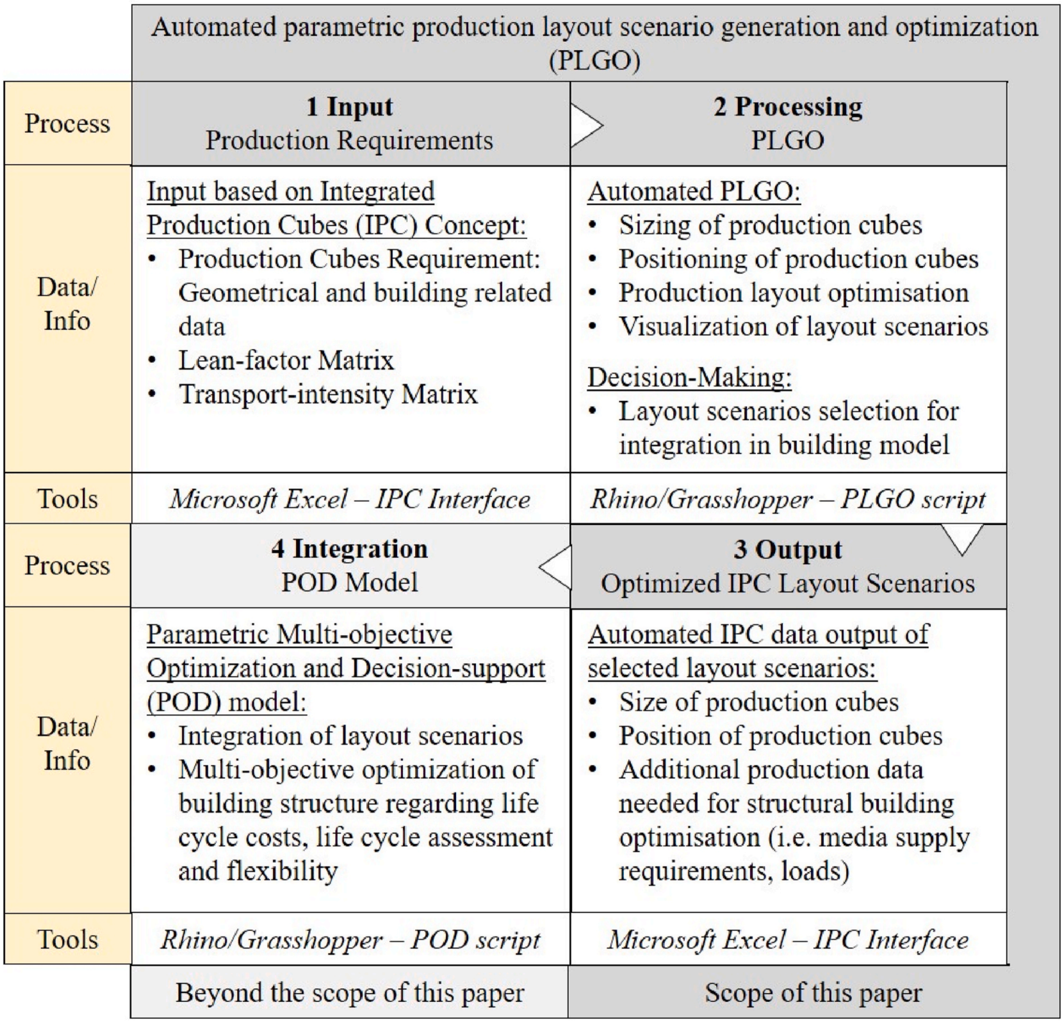
planning and analyze the interrelation to architectural, structural and technical building service data. Additional interviews with production planners served to gather the preferences, knowledge and experience of domain experts.

The results of the state-of-the-art analysis through literature review and the multiple case study are combined in the representation of the design space for PLGO and serve as foundation for a novel integrated production cubes concept (see section 4.1) for parametric production layout planning. The design space representation and the integrated production cubes concept was translated into a parametric framework for PLGO that enables automated generation and multi-objective optimization of production layout scenarios with quantitative objective assessment and layout visualization in real-time. The parametric framework is developed in the visual programming tool Grasshopper for Rhino3D [83] and the developed evolutionary algorithm for multi-objective optimization of production layouts is implemented in a C# component. The integrated production cubes concept and the parametric PLGO framework is tested on a pilot-project of a hygiene production facility. First, a sensitivity analysis is carried out, solving the optimization problem under different relative weighting of the single objectives to validate the defined constraints and objectives. Second, the integrated production cubes concept, the PLGO framework and the multi-objective evolutionary algorithm is validated with equal objective weighting in a comparative study. Third, the PLGO design process and framework is performed with the real production planners from this specific test case to receive feedback on the method and the generated layout solutions.

Our PLGO framework is part of the research project BIMFlexi. In BIMFlexi we aim to develop a holistic digital platform for design and optimization of flexible industrial buildings by integrating building and production processes and models [25]. Besides the parametric production layout optimization method presented in this paper, a parametric design process for automated structural optimization and quantitative flexibility assessment of industrial buildings was developed and presented in Reisinger et al. [79]. In our future research we aim to combine those two frameworks to develop a holistic parametric multi-objective optimization and decision support (POD) model for flexible integrated industrial building design. The integration of the production layout scenarios into the POD model is beyond the scope of this paper and will be presented in our future research steps.

4. Production layout generation and optimization (PLGO) framework

This chapter presents the developed integrated production cubes concept as basis for parametric production layout planning and the PLGO framework. Fig. 2 presents the workflow of the parametric framework with process steps, assigned data and information and applied tools. The description of production requirements is performed manually in the excel-based integrated production cubes (IPC) interface. The integrated production cubes concept respects two relation matrices to describe the production flow. Besides the production cube geometry and production-specific information, building related data such as the expected loads from machines and geometry and loads from necessary building service equipment and media supply, relevant for later building optimization, are inte-



Automated parametric production layout scenario generation and optimization (PLGO)

Process	**1 Input** Production Requirements	**2 Processing** PLGO
Data/ Info	Input based on Integrated Production Cubes (IPC) Concept: • Production Cubes Requirement: Geometrical and building related data • Lean-factor Matrix • Transport-intensity Matrix	Automated PLGO: • Sizing of production cubes • Positioning of production cubes • Production layout optimisation • Visualization of layout scenarios Decision-Making: • Layout scenarios selection for integration in building model
Tools	*Microsoft Excel – IPC Interface*	*Rhino/Grasshopper – PLGO script*
Process	**4 Integration** POD Model	**3 Output** Optimized IPC Layout Scenarios
Data/ Info	Parametric Multi-objective Optimization and Decision-support (POD) model: • Integration of layout scenarios • Multi-objective optimization of building structure regarding life cycle costs, life cycle assessment and flexibility	Automated IPC data output of selected layout scenarios: • Size of production cubes • Position of production cubes • Additional production data needed for structural building optimisation (i.e. media supply requirements, loads)
Tools	*Rhino/Grasshopper – POD script*	*Microsoft Excel – IPC Interface*
	Beyond the scope of this paper	Scope of this paper

Fig. 2. Design process, data and tools of the parametric PLGO framework and scope of the paper.

grated. A direct link between the IPC interface and the parametric PLGO script is developed, automatically transferring the data to Grasshopper to be respected in the optimization process. In the PLGO script, the evolutionary algorithm is defined by the integrated production cubes concept, constraints and objectives. By appropriate sizing and positioning of the production cubes, the algorithm generates multiple different layout scenarios and ranks them according to a constraint violation check and the multi-objective fitness-rating. After the layout scenario generation, the design team has to select preferred layout scenarios, which should be further investigated in the structural building design process. The PLGO script collects generated data of the chosen scenarios such as new geometry details and positions of production cubes and automatically transfers them into the IPC interface, where data is stored. At each research step care was taken to ensure that the developed PLGO framework follows the same design rules as the parametric framework for structural industrial building optimization [79]. This ensures the successful integration of the generated production layout scenarios into the POD model for integrated industrial building design in our future research steps.

4.1. Integrated production cubes concept

A novel integrated production cubes concept is developed as foundation for the parametric production layout generation algorithm. Our concept is based on the research from Smolek et al. [84], who subdivide the overall production plant system into well-defined, manageable modules, so-called “cubes”, from an energy perspective. The geometrical description and spatial arrangement of such production cubes follow the definitions presented in Reisinger et al. [79]. One production cube is defined as a rectangular, orthogonal volume that is described by three variables $C_p\{a_p,b_p,c_p\}$. Each cube is allocated to a specific production function (procurement, manufacturing, distribution) and describes a specific sub-process (i.e. storage, milling). Besides the geometrical information, the concept integrates additional data such as associated loads, media supply, machines or special demands needed for structural optimization later on. The combination of the production cubes represents the production boundary, the production process and thus the production layout. Fig. 3 presents the integrated production cubes concept with the geometrical description of the production cubes and the integrated data for input (before optimization) and output (after optimization).

The production process and material flow, determining the spatial arrangement and the functional sequence of the production cubes and their dependencies, is respected in the optimization by means of two relation matrices – the lean-factor matrix and the transport-intensity matrix (see Fig. 4). The lean-factor matrix defines the neighborhood condition of production cubes by absolutely necessary (AN), important and core (IMPC), unimportant/indifferent (UND) or undesirable (UNIMP). The number of required depen-

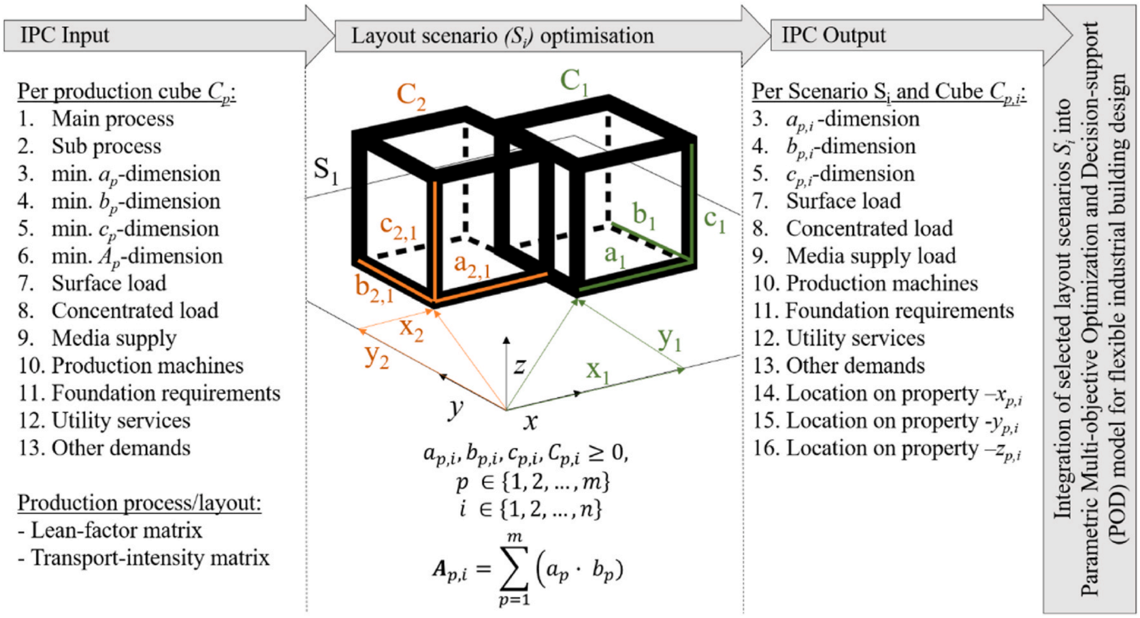
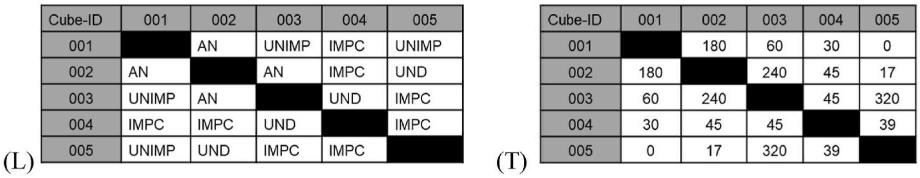


Fig. 3. Integrated production cubes concept: Geometrical formulation and respected data.


(L)

Cube-ID	001	002	003	004	005
001	■	AN	UNIMP	IMPC	UNIMP
002	AN	■	AN	IMPC	UND
003	UNIMP	AN	■	UND	IMPC
004	IMPC	IMPC	UND	■	IMPC
005	UNIMP	UND	IMPC	IMPC	■

(T)

Cube-ID	001	002	003	004	005
001	■	180	60	30	0
002	180	■	240	45	17
003	60	240	■	45	320
004	30	45	45	■	39
005	0	17	320	39	■

Fig. 4. Examples of the production process description within the integrated production cubes input by defining the lean-factor matrix (L) and the transport-intensity matrix (T) before the optimization.

dencies in the cost function is defined by the count of IMPC values in the lean-factor matrix. The transport-intensity matrix describes the frequency of needed transports, i.e. number of materials transports per day, among the production cubes.

4.2. PLGO framework development – constraints and objectives

To develop the PLGO framework, thus the evolutionary algorithm, five constraints and five objectives were defined based on the concept of integrated production cubes. We deal with a facility layout problem that seeks to find non-overlapping geometry and a group of interrelated volumes. We handle this problem with introducing five constraints during optimization to discover feasible design solutions in the search. The production cubes will be evaluated against their positioning, interrelation and geometry such as (c_1) a cohesive layout, (c_2) layout positioning inside the building area, (c_3) lean-factor neighborhood absolutely necessary (c_4) lean-factor neighborhood undesirable and (c_5) adherence of minimum dimensions ($a_{p,min}$,$b_{p,min}$) of the production cubes. The objectives considered in the PLGO framework rely on a combination of the expert interview results and the flexibility criteria proposed in the literature review. The PLGO objectives defined in the study and respected in the multi-objective evolutionary algorithm are: (g_1) maximize the free building area, (g_2) maximize the layout density, (g_3) minimize ratio difference of planned and optimized cube dimensions, (g_4) maximize lean-factor-matrix rating and (g_5) minimize the transport-intensity-matrix length. Table 1 shows the set of constraints and Table 2 describes the five objectives implemented in the PLGO framework.

4.2.1. Fitness function for multi-objective optimization

The problem we aim to solve is a multi-objective optimization problem. In order to investigate the design space and to find optimized production layout scenarios for IIBD a multi-objective evolutionary algorithm is used. In this study the fitness function is mini-

Table 1
Set of constraints in the parametric PLGO framework.

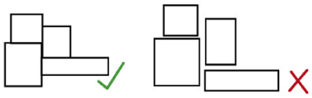
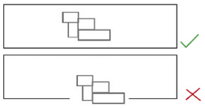
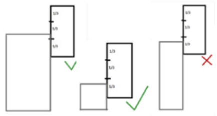
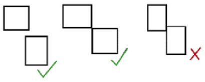
C	Constraints	Formulation	Description
c_1	*Cohesive layout:* The individual production cube areas (A_q, A_r) must not overlap with each other.	$A_q \cap A_r = \varnothing$ with $q \neq r$ and $q, r = \{1,2, \ldots,m\}$ At least one edge of each cube must overlap with another cube.	
c_2	*Building area boundary:* enclosing rectangle of all production cube boundaries R_p must be included into building area boundary R_b.	$\cup_{(p=1)}^{m} R_p \subseteq R_b$	
c_3	When *lean-factor* neighborhood is *absolutely necessary*: the edges of the marked production cubes must overlap by at least 1/3.	Min. 1/3 of shorter cube edge must overlap with the other cube edge	
c_4	*Lean-factor* neighborhood *undesirable:* marked production cubes must not correlate.	Production cubes must not have contact with each other	
c_5	Adherence of minimum dimension of production cubes	$a_{p,min} \leq a_p$ $b_{p,min} \leq b_p$	

Table 2
Objectives considered in the multi-objective optimization in the PLGO framework.

Nr	Objective	Mathematical objective formulation
g_1	*Maximize the free building area:* for future expansion possibility of the production system	$g_1 = \left(\frac{\sum_{p=1}^{m} (a_p * b_p)}{\sum_{p=1}^{m} (a_{p,\ min} * b_{p,\ min})} - 1 \right)$
g_2	*Maximize the layout density:* minimize non-useable area between all cubes to avoid unnecessary transport ways	$g_2 = \left(1 - \frac{\sum_{p=1}^{m} (a_p * b_p)}{A_r} \right)$ A_r… area inside the production space boundary R_p
g_3	*Minimize the ratio difference* of planned cube dimensions (input) and optimized cube dimensions (output)	$g_3 = \frac{\sum abs \left(\frac{\min(a_{p,min},b_{p,min})}{\max(a_{p,\ min},b_{p,\ min})} - \frac{\min(a_p,b_p)}{\max(a_p,b_p)} \right)}{m}$
g_4	*Maximize the rating of the lean- factor-matrix*	$g_4 = 1 - \left(\frac{lfr}{\left(\sum_{p=1}^{m} \sum_{q=p}^{m} L_{p,q}\right)} \right)$ *lfr* … lean-factor rating (number of fulfilled dependencies)
g_5	*Minimize the length of the transport-intensity-matrix*	$g_5 = \frac{\left(\sum_{p=1}^{m} \sum_{q=p}^{m} \left(abs\left(x_p - x_q\right) + abs\left(y_p - y_q\right)\right) \ * T_{p,q} \right)}{\left(\sum_{p=1}^{m} \sum_{q=p}^{m} T_{p,q}\right) * \ (a_s + b_s)}$ $a_s,\ b_s$… dimension of R_p

mized and consists of the five presented PLGO objectives. The fitness function is mathematically described in equation (1), whereby f_o is the cost function; g_i describes each objective and w_i is the related weighting $(w_{1-5} = 0.2)$. An equal weighting of all objectives is applied in the test case to make them testable and comparable.

$$f_o(x) = \sum_{i=1}^{5} g_i * w_i \tag{1}$$

4.3. PLGO framework implementation into parametric model

As described previously, the IPC input data is automatically imported into the developed parametric script in Grasshopper for Rhino3D and serves as input for optimization. The multi-objective layout generation and optimization uses an evolutionary algorithm, implemented in a C# component. In order to find suitable layouts the scalarization method is applied to calculate the fitness. Population size, number of generations and the weights for the fitness can be adjusted directly in the script. The layout generation algorithm does not guarantee that layouts do not violate constraints, therefore constraint violation is penalized and inadequate scenarios removed during the generation process. The algorithm ranks the layouts by constraint penalty first and fitness value second. Fig. 5 presents the parametric script, developed in Grasshopper for Rhino3D and the implemented PLGO algorithm.

5. Test case

This section presents the conducted test case and the performed sensitivity analysis to demonstrate the suitability of the integrated production cubes concept, to evaluate the parametric PLGO framework and to validate the defined constraints and objectives. The proposed framework is tested on a real hygiene production facility located in Austria, which was chosen because of the high density of available information and data. The data provided includes the actual built production layout and data such as production cubes information, the lean-factor matrix and the transport intensity matrix. The total production layout area is 12 724 m^2 and the possible building area is 59 136 m^2. The real production layout, its sub-process requirements (production cube information, lean-factor matrix and transport-intensity matrix) and the building area conditions are used as input for the IPC interface. Each objective weighting setting results in different production layout plans. The defined objectives and constraints are first tested in a sensitivity analysis, performing the multi-objective optimization problem multiple times under different weightings for each objective. Second, for better evaluation of the PLGO framework the generated production layouts received from the collective objectives with an equal weighting are compared with the real planned production layout from the facility.

5.1. Production program and activities

The following Figures and Tables present the input data for the conducted test case. Fig. 6 shows the production program with minimum necessary production cube dimensions and the real planned production layout of the test case. The Cube IDs are composed of two digits: the first number represents the main process each production cube is assigned to (1 = procurement, 2 = manufacturing, 3 = distribution, 4 = other) and the second number reflects the enumerated cubes within its main process.

Table 3 provides both informational matrices, the lean-factor matrix and the transport-intensity matrix. The first row and the first column display the production cube IDs. The entries above the black marked diagonal present the input of the adjacencies among the production cubes, while the entries below the black marked diagonal show the required transport intensity among the cubes.

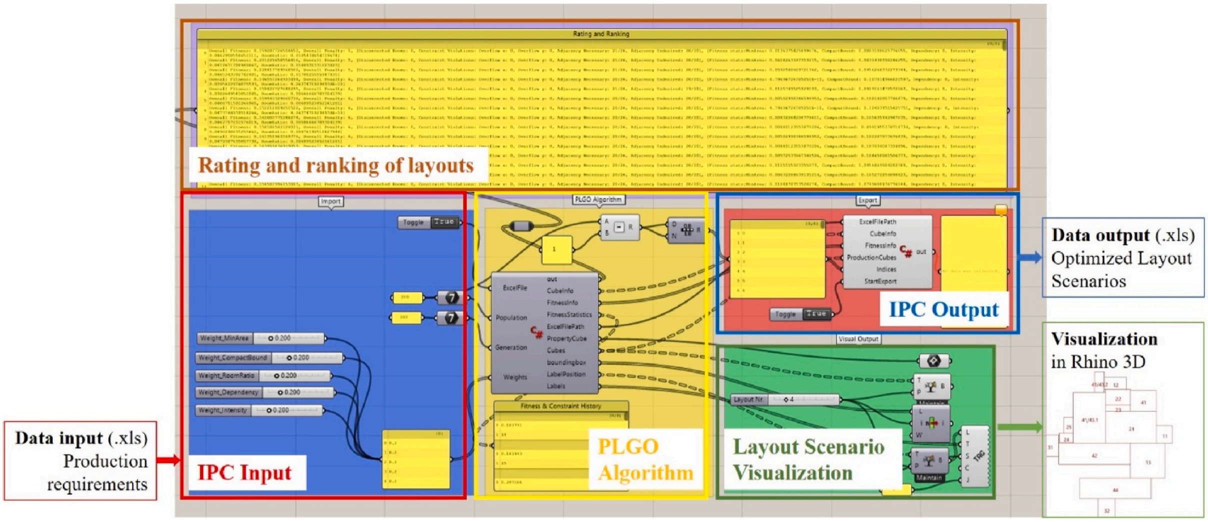
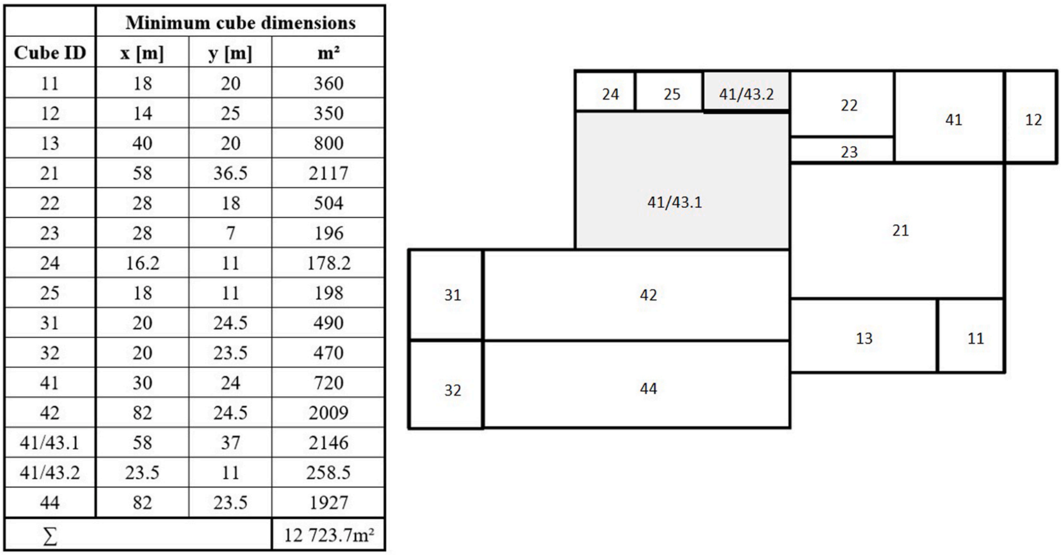


Fig. 5. The parametric PLGO framework in Grasshopper for Rhino 3D, describing the data flow of input and output and the layout visualization in Rhino 3D.



Cube ID	Minimum cube dimensions		
	x [m]	y [m]	m²
11	18	20	360
12	14	25	350
13	40	20	800
21	58	36.5	2117
22	28	18	504
23	28	7	196
24	16.2	11	178.2
25	18	11	198
31	20	24.5	490
32	20	23.5	470
41	30	24	720
42	82	24.5	2009
41/43.1	58	37	2146
41/43.2	23.5	11	258.5
44	82	23.5	1927
∑			12 723.7m²

Fig. 6. Real production layout of the test case from the hygiene production and production cubes requirements of minimum dimensions of each production cube with its main and sub process.

Table 3
Input for the lean-factor matrix (above the diagonal) and transport-intensity matrix (below the diagonal).

	11	12	13	41	42	41/43.1	44	21	22	23	24	25	31	32	41/43.2
11		UNIMP	AN	IMPC	UNIMP	UNIMP	UNIMP	AN	IMPC	IMPC	UND	UND	UND	UND	UNIMP
12	0		UNIMP	AN	UNIMP	UNIMP	UNIMP	UND	UND	IMPC	UND	UND	UND	UND	UNIMP
13	0	0		UNIMP	AN	UNIMP	AN	AN	UND	UND	UND	UND	UND	UND	UNIMP
41	1750	12500	0		IMPC	IMPC	UNIMP	AN	AN	AN	UNIMP	UPNIM	IMPC	IMPC	IMPC
42	0	0	36250	0		AN	AN	AN	UND	UND	UNIMP	UNIMP	AN	IMPC	IMPC
41/43.1	0	0	17750	0	0		IMPC	AN	AN	AN	AN	AN	IMPC	IMPC	AN
44	0	0	0	0	0	0		IMPC	UIMP	IMPC	IMPC	UNIMP	IMPC	AN	UINMP
21	0	0	0	6250	0	6750	45250		UND	AN	UNIMP	UNIMP	UNP	UND	UNIMP
22	0	0	0	1250	0	1500	8750	0		AN	UNIMP	UNIMP	UND	UND	AN
23	0	0	0	125	0	125	1000	0	0		UNIMP	UNIMP	UND	UND	UNIMP
24	0	0	0	0	875	0	0	0	0	0		AN	UNIMP	UNIMP	UNP
25	0	0	0	0	375	0	0	0	0	0	0		UNIMP	UNIMP	AN
31	0	0	0	0	20000	0	37500	0	0	0	0	0		AN	IMPC
32	0	0	0	0	16250	0	18750	0	0	0	0	0	0		IMPC
41/43.2	0	0	17750	0	0	17750	0	0	0	0	0	0	0	0	

5.2. Sensitivity analysis of objectives and constraints

A sensitivity analysis was carried out to assess the sensitivity of the objectives and constraints implemented in the evolutionary multi-objective optimization algorithm. For the sensitivity analysis the multi-objective optimization problem was performed five times, thereby weighting each objective (g1 to g5) individually with 100% (see equation (2)). This enabled the analysis of the influence of each objective definition on the overall results.

$$f_o(x) = g_i * 1.0 \cdot with \cdot i = 1, \dots, 5 \qquad (2)$$

Performing the optimization, the chosen population size for the test case was 200 with 100 generations. The algorithm's time needed to generate 200 layout variants with this setting sum up to 100 s. The algorithm penalizes constraint violations and removes inadequate scenarios during the generation process. It ranks the found layout solutions according to the constraint violation check first. Then the best-performing layout scenarios within the constraint check are rated according to their fitness. The reason to do the constraint check at first hand is to only find scenarios which best meet the set of constraints. Table 4 presents the results of the five best-rated layout scenarios of each individual objective weighting, presenting the constraint check as well as the final fitness rating results of each generated layout scenario. The optimization was carried out five times, weighting every objective once 100%.

Each objective weighting setting results in different production layout plans. In the sensitivity analysis, the multi-objective optimization problem was performed five times under the weighting of 100% for each objective. The sensitivity analysis allowed us to analyze the performance and accuracy of each objective and constraint formulation by examining the optimization results for each objective. The results, presented in Table 4, show that no matter which objective was considered individually, the algorithm finds layout scenarios that comply with the defined constraints c1, c2, c4 and c5. Thus, the algorithm succeeded consistently to produce cohesive

Table 4

Results of the sensitivity analysis: Each objective was once weighted with 100% and the five best-rated generated layouts examined and compared. The red marked table fields highlight the "worst" results and the green marked fields feature the "best" performing results. Every column g1 to g5 represents one run of the algorithm. The rows Layout 0,i to Layout 5,i present the five best individuals.

		Optimization results of $f(x)=g_{,i}*1.0$ with i=1,…,5				
		g1 (w_1=1.0)	g2 (w_2=1.0)	g3 (w_3=1.0)	g4 (w_4=1.0)	g5 (w_5=1.0)
Layout $0_{,i}$	$c1_{,i}$	✓	✓	✓	✓	✓
	$c2_{,i}$	✓	✓	✓	✓	✓
	$c3_{,i}$	21/26	23/26	21/26	19/26	19/26
	$c4_{,i}$	24/24	24/24	24/24	24/24	24/24
	$c5_{,i}$	✓	✓	✓	✓	✓
	$f(x)_{,i}$	$6,46*10^{-3}$	$4,95*10^{-1}$	$2,13*10^{-9}$	$4,00*10^{-1}$	$1,20*10^{-1}$
Layout $1_{,i}$	$c1_{,i}$	✓	✓	✓	✓	✓
	$c2_{,i}$	✓	✓	✓	✓	✓
	$c3_{,i}$	20/26	22/26	21/26	19/26	19/26
	$c4_{,i}$	24/24	24/24	24/24	24/24	24/24
	$c5_{,i}$	✓	✓	✓	✓	✓
	$f(x)_{,i}$	$2,40*10^{-10}$	$4,09*10^{-1}$	$2,13*10^{-9}$	$4,00*10^{-1}$	$1,29*10^{-1}$
Layout $2_{,i}$	$c1_{,i}$	✓	✓	✓	✓	✓
	$c2_{,i}$	✓	✓	✓	✓	✓
	$c3_{,i}$	20/26	22/26	21/26	19/26	19/26
	$c4_{,i}$	24/24	24/24	24/24	24/24	24/24
	$c5_{,i}$	✓	✓	✓	✓	✓
	$f(x)_{,i}$	$2,40*10^{-10}$	$4,47*10^{-1}$	$1,33*10^{-2}$	$6,00*10^{-1}$	$1,30*10^{-1}$
Layout $3_{,i}$	c1,i	✓	✓	✓	✓	✓
	c2,i	✓	✓	✓	✓	✓
	c3,i	20/26	22/26	21/26	18/26	19/26
	c4,i	24/24	24/24	24/24	24/24	24/24
	c5,i	✓	✓	✓	✓	✓
	f(x),i	$2,40*10^{-10}$	$4,68*10^{-1}$	$2,14*10^{-2}$	$3,50*10^{-1}$	$1,34*10^{-1}$
Layout $4_{,i}$	c1,i	✓	✓	✓	✓	✓
	c2,i	✓	✓	✓	✓	✓
	c3,i	20/26	22/26	21/26	18/26	19/26
	c4,i	24/24	24/24	24/24	24/24	24/24
	c5,i	✓	✓	✓	✓	✓
	f(x),i	$6,46*10^{-3}$	$4,91*10^{-1}$	$2,38*10^{-2}$	$4,50*10^{-1}$	$1,36*10^{-1}$

layout solutions that respect the mandatory minimum dimensions of the production cubes and do not exceed the outer limits of the building area. All generated layout scenarios satisfy the constraint that certain production cubes must not correlate when the neighborhood is set as undesirable in L. Constraint c3 aims to guide the algorithm to find layout solutions where specific production cubes do correlate with each other and must be in a direct neighborhood with at least 1/3 of the shorter cube edge. The sensitivity analysis results show that our algorithm could not find a layout scenario where all "absolutely necessary" dependencies of the lean-factor matrix can be met. While in the optimization run of the objectives g4 (maximize the lean-factor matrix) and g5 (minimize the lengths of the transport-intensity matrix) the constraint c3 always performs the worst result, the objective g2 (maximize the layout density) performs the best results regarding the necessary cube dependency. This phenomenon can also be seen in the visualization of the layouts in Fig. 7. Fig. 7 visualizes the generated layout scenarios with the PLGO framework of each optimization run under individual objective weighting. Objective 2 produces very dense layouts, which can lead to better adherence to dependencies. While 26 production cubes interrelations were defined with "absolutely necessary", the algorithm could only find one solution that respects 23 adjacencies by maximizing the layout density. A test run was conducted where all production cubes where adjusted according to the necessary neighborhood requirement, highlighting that c3 is conflicting with c4 and c5. Our algorithm could not find a solution, which respects all 26 desired adjacencies without disrespecting either the mandatory minimum cube dimensions or the undesired adjacencies among production cubes. In almost every case, objective g1, which aims to maximize the free building area for future expansion possibility of the production system, performs the lowest fitness rating in the cost function. The highest fitness rating of the cost function is always observed at objective g2, which aims to maximize the layout density. Yet, objective g4 that searches layout scenarios with maximum rating of the lean-factor matrix also results in relatively high ratings of the cost function. The comparison of the cost function results

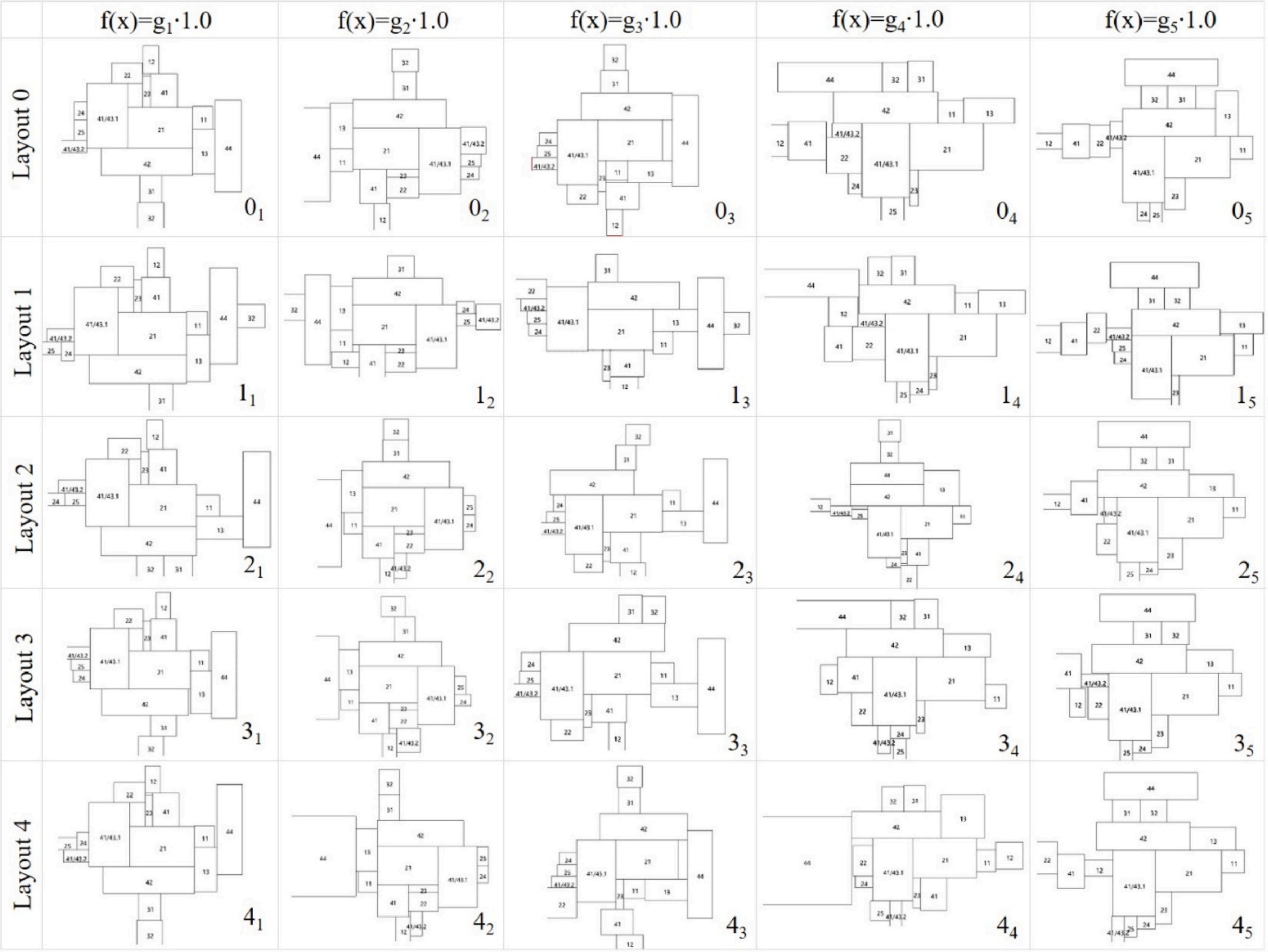


Fig. 7. Visualization and comparison of the generated best-rated layouts received from the sensitivity analysis per weighting scenario.

of the individual objectives displays that in the multi-objective optimization problem the objectives g1 and g3 significantly contribute to minimize the cost function, while the objectives g2, g4 and g5 add to higher cost function results.

5.3. PLGO framework test – multi-objective optimization with equal objective weighting

The chosen population size was 200 with 100 generations to test the PLGO framework and compare the automated generated layout scenario results under equal objective weighting with the real test case. The PLGO algorithm provided 200 different layouts, while the parametric PLGO framework visualized the five best-rated layout scenarios. Fig. 8 shows the comparison of the best-rated layout scenarios using the PLGO framework and the real layout.

Table 5 presents the ranking results for the constraint violation check and the results of the fitness rating of the best-rated layout scenarios produced by the PLGO algorithm. Layout 0 represents the best performing scenario as it has the smallest fitness within the least number of constraint violations. Layout 1 and 2 contain three of the best-rated objectives. Layout 1 performs the overall best-rated cost function, while containing the worst rated objective in g4. The least-rated cost function results from Layout 4, which also consists of four worst rated single objectives (g1, g2 and g5). The conducted test case failed to find layout scenarios which meet all constraints as the PLGO algorithm could not find a solution to fully fulfill constraint c3, placing all production cubes according to the desired adjacency. The algorithm was able to find a layout in which 21 of the 26 necessary direct dependencies are found. Objective g3, which aims to maximize the lean-factor matrix, performs the highest results within each layout scenario, while g1 and g5 are the objectives with the lowest performance rating in the study.

Table 6 shows the comparison results of the pre-defined minimum dimensions of the cubes obtained from the test case and the generated cubes dimensions of the best-ranked layout 0 obtained from the multi-objective optimization. The PLGO algorithm increased the dimensions of only one cube (cube 24), which results in an increase of the total production area of only 0.6%.

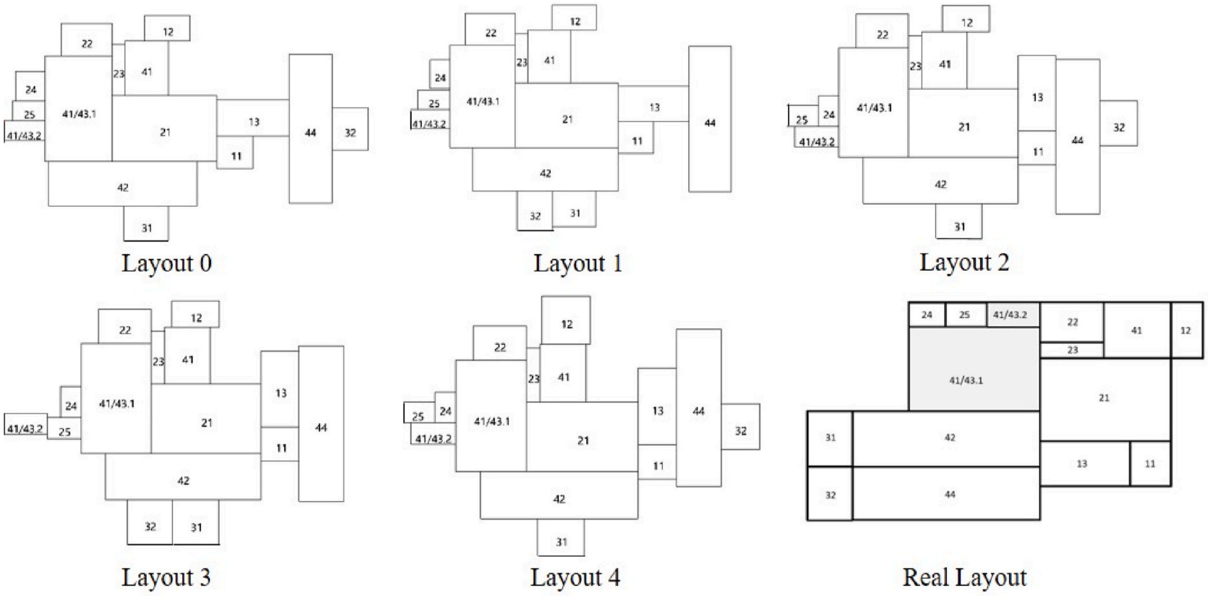


Fig. 8. Best-rated layout scenarios generated and the real layout of the test case.

Table 5
Constraint violation check and results of the single objective evaluation and the final fitness rating of the best-rated layout scenarios.

PLGO framework test results of the best 5 generated layout scenarios						
		Layout 0	Layout 1	Layout 2	Layout 3	Layout 4
Constraint violation check	**c1**	✓	✓	✓	✓	✓
	c2	✓	✓	✓	✓	✓
	c3	21/26	20/26	20/26	20/26	20/26
	c4	24/24	24/24	24/24	24/24	24/24
	c5	✓	✓	✓	✓	✓
Fitness rating	**g1**	$1.32*10^{-3}$	$4.79*10^{-11}$	$4.797*10^{-11}$	$3.02*10^{-3}$	$5.64*10^{-3}$
	g2	0.098	0.091	0.091	0.089	0.105
	g3	0.12	0.10	0.12	0.11	0.12
	g4	0.049	0.051	0.044	0.045	0.046
	g5	$4.28*10^{-3}$	$4.26*10^{-10}$	$4.26*10^{-10}$	$4.43*10^{-3}$	$5.87*10^{-3}$
	$f(x) = \sum g_i$	0.274	0.242	0.256	0.257	0.274

Table 6
Comparison of the pre-defined minimum dimensions of the cubes obtained from the test case and the actual cubes dimensions from Layout 0 generated by the PLGO algorithm.

Cube ID	Comparison of the real test case and the generated cube dimensions of layout 0								
	Specified minimum			Algorithm output			Δ		
	x [m]	y [m]	m^2	x [m]	y [m]	m^2	x [m]	y [m]	m^2 [%]
11	18	20	360	20	18	360	+2	−2	±0
12	14	25	350	25	14	350	+11	−11	±0
13	40	20	800	40	20	800	±0	±0	±0
21	58	36,5	2117	58	36.5	2117	±0	±0	±0
22	28	18	504	28	18	784	±0	±0	±0
23	28	7	196	7	28	196	−21	+21	±0
24	16.2	11	178,2	16.2	16.2	262.44	±0	+5,2	+47.3
25	18	11	198	18	11	198	±0	±0	±0
31	20	24.5	490	24.5	20	490	+4.5	−4.5	±0
32	20	23,5	470	20	23.5	470	±0	±0	±0
41	30	24	720	24	30	720	−6	+6	±0
42	82	24.5	2009	82	24.5	2009	±0	±0	±0
41/43.1	58	37	2146	37	58	2146	−21	+21	±0
41/43.2	23.5	11	258,5	23.5	11	531,1	±0	±0	±0
44	82	23.5	1927	23.5	82	1927	−58.5	+58.5	±0
		∑	12 723.7m^2		∑ (**Δ**)	12 807.9m^2	−89.9 m	+88.2 m	+0.6%

6. Discussion

The purpose of the presented research was the development and test of the design space and the parametric framework for automated production layout generation and optimization (PLGO), respecting production, building and flexibility requirements. An exploratory multiple case study composed of expert interviews and a use case study served for the development of the PLGO design space. The definition of a novel integrated production cubes concept enabled the development of a parametric production layout planning method that can be directly integrated into parametric building design processes. For the automated generation and optimization of the production layouts, a multi-objective evolutionary algorithm was implemented into the parametric design process. By testing the framework on a pilot-project of a hygiene production facility, the PLGO framework and the multi-objective evolutionary algorithm could be validated and evaluated. Comparing layout 0 with the real production layout of the test case one can see that the generated layout is not as compact as the real layout. This may occur because the algorithm could not find a solution that fulfills constraint c3. Results reveal that the objectives g1 and g2 are highly conflicting goals. While layout 3 meets the lowest fitness-rating for objective g2, aiming to maximize the layout density, layout 1 and 2 perform better fitness-results at objective g1, aiming to maximize the free building area for future possible expansion. At this state, it would be up to the decision-maker which layout will be chosen or a user-specific objective weighting can be set before the simulation. The definition and correlation of objective g1 and g2 should be further investigated in future research. Constraint c5 is a non-violable constraint, meaning that all minimum dimensions from the real layout input are also kept in the generated layout scenario. The dimension of all production cubes generated in layout 0 are the same dimensions as in the real layout, except for production cube 24, the algorithm decided on a larger dimension in the layouts y-dimension in order to come to a feasible solution. Among the production cubes 21 and 44 the input was set to the highest transport intensity. However, the algorithm generates a scenario in the best-rated Layout 0, which positions another cube (cube 13) between the two. This is due to the fact that the lean-factor matrix states the adjacency status of important and core between cube 21 and 44. The findings indicate that the algorithm works as intended, respecting the set of input values and maximizing the lean-factor matrix in objective g4. Constraint c3 considers the lean-factor matrix and the neighborhood of absolutely necessary. According to the real layout, the neighborhood of absolutely necessary was set for 26 production cubes. However, constraint 3 is only fulfilled 21 times within the conducted test run. The algorithm could not find a solution respecting all adjacency requirements. The test to find layout scenarios that meet all the desires of constraint 3 failed. Thus, in future research a constant priority could be introduced to determine the importance of each constraint.

The proof-of-concept demonstrates that the PLGO framework enables the automated generation and optimization of feasible production layout scenarios with quantitative objective assessment and layout visualization. The presented algorithm took a maximum of 100 s to complete the multi-objective optimization problem with a population size of 200 populations with 100 generations, producing 200 layout scenarios. Due to the multi-objective problem complexity, the developed parametric evolutionary approach showed good performance in a short time, while time is an important key in real world applications. Currently, the final choice of which layout scenarios should be further investigated in the building design process is still semi-automated, as the designer must choose the preferred layouts. The circumstance of manual layout selection after the optimization is explicitly intended in this research as it allows the inclusion of human knowledge and expertise in the design process, not having to rely only on the best-rated scenarios generated by the computational algorithm. However, interactive algorithms often execute slowly because they require the intervention of human experts [16], yet, can greatly contribute to improve optimized designs by involving the decision maker in the search for a satisfying solutions. The decision maker may want solutions that have, i.e. all the remaining space either concentrated in a determined location or distributed in certain areas of the plant as presented in García-Hernández et al. [65]. Currently, our PLGO algorithm arranges each cube randomly within the entire area of the given plot and does not consider specific cubes location preferences. Hence, in practice it is required to position and fix certain production areas at specific locations and to consider traffic routes and truck turning areas on the plot. A potential goal for future research would be to use the PLGO framework to generate training data for a machine learning pipeline and integrate prior human knowledge into the model. Prior human knowledge can be integrated in various ways. The two most important ones are first to augment the data and second to penalize or weight the cost function to better learn and capture the intrinsic properties of the data. Our evolutionary algorithm is capable of generating a large number of layout outputs in a short time. Training data can be collected by encoding the designer's feedback on the generated layout outputs. With our inputs and the modified layouts that respect designer's knowledge, a machine learning model can be developed. The extension of our framework by including a machine learning model that learns from our data and integrates prior-human knowledge would predict layouts that are closer to designer intentions and fasten the optimization process.

In current practice, the assignment of objects within factory buildings is mainly conducted manually without quantitative feedback on generated layouts [10]. Many iteration steps are necessary to receive ideal layouts. Only in the second planning step, the creation of the real layout plan, additional design aspects are usually considered. Most optimization models in FLP research just consider material handling costs and rearrangement costs, while factors like closeness ratings among departments and layout flexibility are often not included [74]. Hence, our developed PLGO framework integrates important production and building related design objectives in the ideal layout planning phase, optimizing the production layouts based on the trade-off between productivity (maximize lean-factor matrix rating, minimize transport-intensity matrix) and building flexibility (maximize free building area, maximize layout density and minimize cube dimension ratio). However, the PLGO framework does currently not respect the most common objectives in FLP - the material handling cost [15,66] and the total completion time [68]. This fact should be taken into account in future research, evolving the PLGO design space by those two objectives, see Fig. 9. Further research is needed to evolve and increase the potential of the PLGO framework for its implementation in real-world scenarios. In this research, a simple input scheme of minimum width and length for each production cube has been employed. This is consistent with previous research, which mostly generates and optimizes rectangular facilities and departments on rectangular floor spaces [51,66,72]. When L-shaped or irregular shaped cubes should be considered, it is challenging to generate a scheme that controls the design of different orthogonal rooms, unless one divides them into rectangles. This current limitation would need to be addressed in future research to generate even more realistic production layouts. Moreover, trends in manufacturing move towards vertical and multi-level production. This study presented a 2-dimensional production layout generation and optimization approach. Multi-level space allocation has been investigated in the field of architecture [53] and structural design [58]. Yet, there is a lack of consistent methods for 3-dimensional cubes arrangement to enable multi-level production, which calls for future research. Finally, from the above analysis, the presented PLGO framework can be seen as a practical

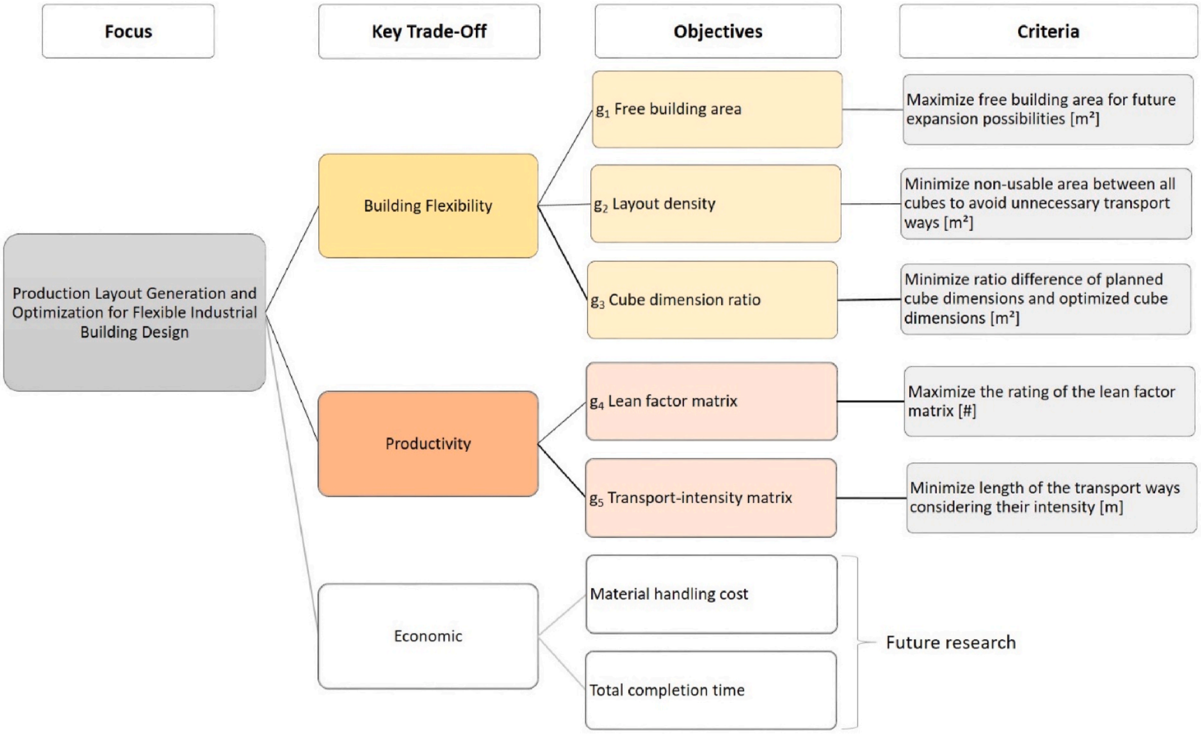


Fig. 9. Key trade-offs and objectives respected in the PLGO framework (yellow and orange boxes) and objectives which can be integrated in future research (white boxes). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

and useful method to integrate complex manufacturing scenarios into building design, to guide design decisions towards increased flexible industrial building solutions.

7. Conclusion

With Industry 4.0, flexible buildings for factory change have become an important research direction. Technology of the future needs to allow changing production layouts, which have to be examined in the early building design stage. Therefore, it is of great significance for future directions to carry out design and optimization studies that coherently respect building and production systems. Based on this idea, a parametric design technique for automated generation, optimization and integration of production layouts has been developed and presented in this paper. The developed methodology enables the mathematical analysis, design and evaluation of production layouts, taking into account industrial building and flexibility criteria. This novel approach allows the production layout not only to ensure operation efficiency, but also to reduce the risk of physical collision with the building structure. Results of the conducted test case show that the generated and optimized layouts create valuable results for integration into building design. Furthermore, the layout results are an important source as basis for subsequent real layout planning steps. The study innovations mainly include three aspects: (1) Evaluation innovation: evaluating production layouts with building and flexibility criteria, (2) Modelling innovation: developing a parametric production layout design approach and (3) Algorithm innovation: presenting a multi-objective evolutionary algorithm that is based on parametric models and integrates production, flexibility and building criteria.

The applied research method of parametric modelling coupled to a multi-objective evolutionary algorithm allows the automated creation of a significant number of layout scenarios according to pre-defined requirements. The results of the test case reveal that the developed PLGO framework is feasible and produces viable layout scenarios to integrate and investigate in parametric building design processes later on. The PLGO framework serves as an applicable and suitable answer for integrated industrial building design, since the optimization generates feasible production layout scenarios, fulfilling the most important requirements and constraints in production layout planning, while also taking into account building aspects. The framework enables fast multidisciplinary decision-making support as design teams receive quick quantitative and visual feedback on the layouts based on the input requirements.

The goal of the presented research is to provide flexible industrial building design solutions that can accommodate a selection of several prioritized production plans. Thus, in the next steps of this research the presented parametric PLGO framework will be coupled to the parametric structural building optimization framework presented in Reisinger et al. [79]. Based on the integration of production and building design models, a holistic parametric multi-objective optimization and decision support model for flexible integrated industrial building design will be developed. The integration of production layout scenarios into the structural design process will allow the evaluation of consequences of changing production layouts on the building structure, enabling integrated multi-objective performance improvement and multidisciplinary decision making support in real-time. The efficiency of the integrated framework, the coupling scheme, the integrated production cubes interface and the performance results will be tested within a user-study with experts. Follow-up studies to implement the PLGO framework into the holistic multi-objective optimization and decision support model will also contribute to further validate the proposed data.

Author contributions

Conceptualization. J.R.; Data curation, M.Z.; Formal analysis, J.R., M.Z., X.S; Funding acquisition, J.R., I.K., H.K.; Investigation, M.Z., J.R.; Methodology: J.R.; Project administration, J.R.; Resources, J.R.; Software, M.Z., X.S; Supervision, I.K., P.K. and H.K.; Validation, J.R. and M.Z.; Visualization, J.R.; Roles/Writing - original draft, J.R.; Writing - review & editing, I.K., P.K., H.K. All authors have read and agreed to the submitted version of the manuscript.

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CRediT author statement

Julia Reisinger: Conceptualization, Formal analysis, Funding acquisition, Investigation, Methodology, Project administration, Resources, Validation, Visualization, Roles/Writing - original draft. Maria Antonia Zahlbruckner: Data curation, Formal analysis, Investigation, Software, Validation. Iva Kovacic: Funding acquisition, Supervision, Writing - review & editing. Peter Kan: Supervision, Writing - review & editing. Xi Wang-Sukalia: Formal analysis, Software, Hannes Kaufmann: Funding acquisition, Supervision, Writing - review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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References

[1] T.D. Oesterreich, F. Teuteberg, Understanding the implications of digitisation and automation in the context of Industry 4.0: a triangulation approach and elements of a research agenda for the construction industry, Comput. Ind. 83 (2016) 121–139.
[2] H. Lasi, P. Fettke, H.-G. Kemper, T. Feld, M. Hoffmann, Industry 4.0, Bus. Inform. Syst. Eng. 6 (2014) 239–242.
[3] F. Flager, The Design of Building Structures for Improved Life-Cycle Performance, Master’s Thesis, Massachusetts Institute of Technology, Cambridge, MA, USA, 2003.
[4] G. Gourlis, I. Kovacic, Building Information Modelling for analysis of energy efficient industrial buildings – a case study, Renew. Sustain. Energy Rev. 68 (2017) 953–963.
[5] G. Ashrae, The design process—early stages, in: The ASHRAE GreenGuide, second ed., vol. 2, Butterworth-Heinemann, Burlington, MA, USA, 2006, pp. 73–100.
[6] T. Zhao, C.-L. Tseng, Valuing flexibility in infrastructure expansion, J. Infrastruct. Syst. 9 (2003) 89–97.
[7] M.-A. Cardin, M. Ranjbar-Bourani, R. De Neufville, Improving the lifecycle performance of engineering projects with flexible strategies: example of on-shore LNG production design, Syst. Eng. 18 (2015).
[8] G. Schuh, A. Kampker, C. Wesch-Potente, Condition based factory planning, J. Inst. Eng. Prod. 5 (2011) 89–94.
[9] M. Ebade Esfahani, P. Burggräf, M. Dannapfel, D. Schneidermann, N. Schwamborn, Integrated factory modelling: using BIM to disrupt the interface between manufacturing and construction in factory planning, WIT Trans. Built Environ. 192 (2019) 143–155.
[10] S.P. Vierschilling, M. Dannapfel, S. Losse, O. Matzke, Generative design in factory layout planning: an application of evolutionary computing within the creation of production logistic concepts, in: Proceedings of 1st Conference on Production Systems and Logistics CPSL 2020, 2020, pp. 147–156, https://doi.org/10.15488/9656.
[11] S.P. Singh, R.R.K. Sharma, A review of different approaches to the facility layout problems, Int. J. Adv. Manuf. Technol. 30 (2006) 425–433.
[12] G. La Scalia, R. Micale, M. Enea, Facility layout problem: bibliometric and benchmarking analysis, Int. J. Ind. Eng. Comput. (2019) 453–472.
[13] L. Garcia-Hernandez, J.A. Garcia-Hernandez, L. Salas-Morera, C. Carmona-Muñoz, N.S. Alghamdi, J.V. De Oliveira, S. Salcedo-Sanz, Addressing unequal area facility layout problems with the coral reef optimization algorithm with substrate layers, Eng. Appl. Artif. Intell. 93 (2020) 103697.
[14] G. Aiello, G. La scalia, M. Enea, A non dominated ranking Multi Objective Genetic Algorithm and electre method for unequal area facility layout problems, Expert Syst. Appl. 40 (2013) 4812–4819.
[15] A.I. Shabaka, H.A. Elmaraghy, A model for generating optimal process plans in RMS, Int. J. Comput. Integrated Manuf. 21 (2008) 180–194.
[16] J.M. Palomo-Romero, L. Salas-Morera, L. García-Hernández, An island model genetic algorithm for unequal area facility layout problems, Expert Syst. Appl. 68 (2017) 151–162.
[17] G. Aiello, M. Enea, G. Galante, A multi-objective approach to facility layout problem by genetic search algorithm and Electre method, Robot. Comput. Integrated Manuf. 22 (2006) 447–455.
[18] M. Purnomo, Y. Wiwoho, Multi-objective Mixed Integer Programming approach for facility layout design by considering closeness ratings, material handling, and re-layout cost, IOP Conf. Ser. Mater. Sci. Eng. 105 (2016) 012045.
[19] D. Nagy, D. Lau, J. Locke, J. Stoddart, L. Villaggi, R. Wang, D. Zhao, D. Benjamin, Project discover: an application of generative design for architectural space planning, in: Proceedings of the Symposium on Simulation for Architecture and Urban Design, vol. 7, 2017, pp. 1–8, https://doi.org/10.22360/simaud.2017.simaud.007.
[20] J. Haymaker, M. Bernal, M.T. Marshall, V. Okhoya, A. Szilasi, R. Rezaee, C. Chen, A. Salveson, J. Brechtel, L. Deckinga, H. Hasan, P. Ewing, B. Welle, Design space construction: a framework to support collaborative, parametric decision making, J. Inf. Technol. Construct. 23 (2018) 157–178.
[21] R. Danhaive, C. Mueller, Combining parametric modeling and interactive optimization for high-performance and creative structural design, in: Proceedings of the International Association for Shell and Spatial Structures (IASS), vol. 20, 2015, pp. 1–11, 17 - 20 August 2015, Amsterdam, The Netherlands.
[22] N.C. Brown, V. Jusiega, C.T. Mueller, Implementing data-driven parametric building design with a flexible toolbox, Autom. ConStruct. 118 (2020) 103252.
[23] W. Pan, M. Turrin, C. Louter, S. Sariyildiz, Y. Sun, Integrating multi-functional space and long-span structure in the early design stage of indoor sports arenas by using parametric modelling and multi-objective optimization, J. Build. Eng. 22 (2019) 464–485.
[24] J. Reisinger, M.A. Zahlbruckner, I. Kovacic, P. Kán, X. Wang-Sukalia, Framework proposal for automated generation of production layout scenarios: a parametric design technique to connect production planning and structural industrial building design, in: Proc. EG-ICE 2021 Workshop on Intelligent Computing in Engineering in Berlin, vol. 28, Universitätsverlag der TU Berlin, 2021, ISBN 978-3-7983-3212-6, pp. 22–33.
[25] J. Reisinger, I. Kovacic, H. Kaufmann, P. Kan, I. Podkosova, Framework proposal for a BIM-based digital platform for flexible design and optimization of industrial buildings for industry 4.0, in: Proc. 37th CIB W78 Information Technology for Construction Conference (CIB W78), 2020, pp. 401–415, https://doi.org/10.46421/2706-6568.37.2020.paper029, São Paulo, Brazil.
[26] N.V. Sahinidis, I.E. Grossmann, Multiperiod investment model for processing networks with dedicated and flexible plants, Ind. Eng. Chem. Res. 30 (1991) 1165–1171.
[27] K.M. Madson, B. Franz, K.R. Molenaar, G. Okudan Kremer, Strategic development of flexible manufacturing facilities, Eng. Construct. Architect. Manag. 27 (2020) 1299–1314.
[28] S.R. De Paris, C.N.L. Lopes, Housing flexibility problem: review of recent limitations and solutions, Front. Architect. Res. 7 (2018) 80–91.
[29] C. Cavalliere, G.R. Dell’osso, F. Favia, M. Lovicario, BIM-based assessment metrics for the functional flexibility of building designs, Autom. ConStruct. 107 (2019) 102925.
[30] C. Cellucci, M. Sivo, The flexible housing: criteria and strategies for implementation of the flexibility, J. Civi. Eng. Architect. 9 (2015) 845–852, https://doi.org/10.17265/1934-7359/2015.07.011.
[31] R. Geraedts, FLEX 4.0, A practical instrument to assess the adaptive capacity of buildings, Energy Procedia 96 (2016) 568–579.
[32] B. Glumac, N. Islam, Housing preferences for adaptive re-use of office and industrial buildings: demand side, Sustain. Cities Soc. 62 (2020) 102379.
[33] J. Browne, D. Dubois, K. Rathmill, S. Sethi, K. Stecke, Classification of flexible manufacturing systems, FMS Mag. 2 (1984) 114–117.
[34] A.K. Sethi, S.P. Sethi, Flexibility in manufacturing: a survey, Int. J. Flex. Manuf. Syst. 2 (1990) 289–328.
[35] H.P. Wiendahl, H.A. Elmaraghy, P. Nyhuis, M.F. Zäh, H.H. Wiendahl, N. Duffie, M. Brieke, Changeable manufacturing - classification, design and operation, CIRP Ann. 56 (2007) 783–809.
[36] A. Moline, Recipe for change: the flexible food processing plant of the future, in: *DesignFlex2030*, Industrial Asset Management Council (IAMC) and SIOR, GA, USA, 2015, Available online: 2015. https://www.sior.com/docs/default-source/defaultdocumentlibrary/DesignFlex2030.pdf. (Accessed 17 September 2021).
[37] A. Moline, Rx for change: the flexible biopharma facility of the future, in: *DesignFlex2030*, Industrial Asset Management Council (IAMC) and SIOR, GA, USA, 2017, Available online: 2017. https://www.sior.com/docs/default-source/white-papers/dflex2 030---rx-forchange.pdf?sfvrsn=0. (Accessed 17 September 2021).
[38] D. Upton, What really makes factories flexible, Harv. Bus. Rev. 73 (1995) 74–85.
[39] J. Reisinger, P. Hollinsky, I. Kovacic, Design guideline for flexible industrial buildings integrating industry 4.0 parameters, Sustainability 13 (2021) 10627.
[40] E. Francalanza, J. Borg, C. Constantinescu, Development and evaluation of a knowledge-based decision-making approach for designing changeable manufacturing systems, CIRP J. Manuf. Sci. Technol. 16 (2017) 81–101.

[41] M. Colledani, T. Tolio, Integrated process and system modelling for the design of material recycling systems, CIRP Ann. 62 (2013) 447–452.
[42] A. Kluczek, An overall multi-criteria approach to sustainability assessment of manufacturing processes, Procedia Manuf. 8 (2017) 136–143.
[43] A.M. Deif, A system model for green manufacturing, J. Clean. Prod. 19 (2011) 1553–1559.
[44] F. Bleicher, F. Duer, I. Leobner, I. Kovacic, B. Heinzl, W. Kastner, Co-simulation environment for optimizing energy efficiency in production systems, CIRP Ann. 63 (2014) 441–444.
[45] D. Chinese, G. Nardin, O. Saro, Multi-criteria analysis for the selection of space heating systems in an industrial building, Energy 36 (2011) 556–565.
[46] G. Gourlis, I. Kovacic, A study on building performance analysis for energy retrofit of existing industrial facilities, Appl. Energy 184 (2016) 1389–1399.
[47] U. Bac, K.A.M.S. Alaloosi, C. Turhan, A comprehensive evaluation of the most suitable HVAC system for an industrial building by using a hybrid building energy simulation and multi criteria decision making framework, J. Build. Eng. 37 (2021) 102153.
[48] F. Ascione, N. Bianco, T. Iovane, G.M. Mauro, D.F. Napolitano, A. Ruggiano, L. Viscido, A real industrial building: modeling, calibration and Pareto optimization of energy retrofit, J. Build. Eng. 29 (2020) 101186.
[49] V. Rodrigues, A.A. Martins, M.I. Nunes, A. Quintas, T.M. Mata, N.S. Caetano, LCA of constructing an industrial building: focus on embodied carbon and energy, Energy Procedia 153 (2018) 420–425.
[50] R.S. Liggett, Automated facilities layout: past, present and future, Autom. ConStruct. 9 (2000) 197–215.
[51] N. Upasani, K. Shekhawat, G. Sachdeva, Automated generation of dimensioned rectangular floorplans, Autom. ConStruct. 113 (2020) 103149.
[52] I.G. Dino, An evolutionary approach for 3D architectural space layout design exploration, Autom. ConStruct. 69 (2016) 131–150.
[53] E. Rodrigues, A.R. Gaspar, Á. Gomes, An approach to the multi-level space allocation problem in architecture using a hybrid evolutionary technique, Autom. ConStruct. 35 (2013) 482–498.
[54] D. Lobos, D. Donath, The problem of space layout in architecture: a survey and reflections, Arquiteturarevista 6 (2010) 136–161.
[55] R. Bausys, I. Pankrašovaite, Optimization of architectural layout by the improved genetic algorithm, J. Civi. Eng. Manag. 11 (2005) 13–21.
[56] D.H. Dorrah, M. Marzouk, Integrated multi-objective optimization and agent-based building occupancy modeling for space layout planning, J. Build. Eng. 34 (2021) 101902.
[57] M. Bilal, L.O. Oyedele, O.O. Akinade, J.M.D. Delgado, L.A. Akanbi, A.O. Ajayi, M.S. Younis, Design optimisation using convex programming: towards waste-efficient building designs, J. Build. Eng. 23 (2019) 231–240.
[58] D.P.H. Claessens, S. Boonstra, H. Hofmeyer, Spatial zoning for better structural topology design and performance, Adv. Eng. Inf. 46 (2020) 101162.
[59] S. Boonstra, K. Van Der Blom, H. Hofmeyer, M.T.M. Emmerich, Conceptual structural system layouts via design response grammars and evolutionary algorithms, Autom. ConStruct. 116 (2020) 103009.
[60] Y. Ojaghi, A. Khademi, N.M. Yusof, N.G. Renani, S.A.H.B.S. Hassan, Production layout optimization for small and medium scale food industry, Procedia CIRP 26 (2015) 247–251.
[61] M.F. Anjos, M.V.C. Vieira, Mathematical optimization approaches for facility layout problems: the state-of-the-art and future research directions, Eur. J. Oper. Res. 261 (2017) 1–16.
[62] A.R. Mckendall, J. Shang, S. Kuppusamy, Simulated annealing heuristics for the dynamic facility layout problem, Comput. Oper. Res. 33 (2006) 2431–2444.
[63] S. Jiang, A.Y.C. Nee, A novel facility layout planning and optimization methodology, CIRP Ann. 62 (2013) 483–486.
[64] F. Azadivar, J. Wang, Facility layout optimization using simulation and genetic algorithms, Int. J. Prod. Res. 38 (2000) 4369–4383.
[65] L. García-Hernández, A. Arauzo-Azofra, L. Salas-Morera, H. Pierreval, E. Corchado, Facility layout design using a multi-objective interactive genetic algorithm to support the DM, Expet Syst. 32 (2015) 94–107.
[66] J. Chae, A.C. Regan, Layout design problems with heterogeneous area constraints, Comput. Ind. Eng. 102 (2016) 198–207.
[67] S. Wang, X. Lu, X.X. Li, W.D. Li, A systematic approach of process planning and scheduling optimization for sustainable machining, J. Clean. Prod. 87 (2015) 914–929.
[68] F.A. Touzout, L. Benyoucef, Multi-objective sustainable process plan generation in a reconfigurable manufacturing environment: exact and adapted evolutionary approaches, Int. J. Prod. Res. 57 (2019) 2531–2547.
[69] J. Li, X. Tan, J. Li, Research on dynamic facility layout problem of manufacturing unit considering human factors, Math. Probl Eng. 2018 (2018) 6040561.
[70] A. Khezri, H.H. Benderbal, L. Benyoucef, Towards a sustainable reconfigurable manufacturing system (SRMS): multi-objective based approaches for process plan generation problem, Int. J. Prod. Res. 59 (2021) 4533–4558.
[71] M.A. El-Baz, A genetic algorithm for facility layout problems of different manufacturing environments, Comput. Ind. Eng. 47 (2004) 233–246.
[72] J.F. Gonçalves, M.G.C. Resende, A biased random-key genetic algorithm for the unequal area facility layout problem, Eur. J. Oper. Res. 246 (2015) 86–107.
[73] A. Shoja Sangchooli, M.R. Akbari Jokar, Obtaining an initial solution for facility layout problem, J. Ind. Math. (2013), https://doi.org/10.1155/2013/130251, Article ID 130251. 10 pages.
[74] P. Pérez-Gosende, J. Mula, M. Díaz-Madroñero, Overview of dynamic facility layout planning as a sustainability strategy, Sustainability 12 (2020) 8277.
[75] E. Motta, Reusable Components for Knowledge Modelling, PhD Thesis. PhD thesis The Open University. Faculty of Science, Technology, Engineering and Mathematics, Knowledge Media Institute, 1998, https://doi.org/10.21954/ou.ro.0000e217.
[76] N.C. Brown, C.T. Mueller, Design for structural and energy performance of long span buildings using geometric multi-objective optimization, Energy Build. 127 (2016) 748–761.
[77] M. Turrin, P. Von Buelow, R. Stouffs, Design explorations of performance driven geometry in architectural design using parametric modeling and genetic algorithms, Adv. Eng. Inf. 25 (2011) 675.
[78] W. Pan, Y. Sun, M. Turrin, C. Louter, S. Sariyildiz, Design exploration of quantitative performance and geometry typology for indoor arena based on self-organizing map and multi-layered perceptron neural network, Autom. ConStruct. 114 (2020) 103163.
[79] J. Reisinger, M. Knoll, I. Kovacic, Design space exploration for flexibility assessment and decision making support in integrated industrial building design, Optim. Eng. (2021).
[80] P. Nourian, S. Rezvani, S. Sariyildiz, Designing with Space Syntax A configurative approach to architectural layout, proposing a computa-tional methodology, in: Spatial Performance and Space Syntax - Volume 1 - Computation and Performance - eCAADe, vol. 31, 2013, pp. 357–366.
[81] R.K. Yin, Case Study Research: Design and Methods, 4.th Edition, SAGE Publications Inc, Los Angeles, CA, 2009.
[82] K. Eisenhardt, Building theories from case study research, Acad. Manag. Rev. 14 (1989) 532–550.
[83] A. Mcneel, Grasshopper [Online], McNeel & Associates, 2020, Available:. https://www.rhino3d.com/6/new/grasshopper. (Accessed 29 January 2020).
[84] P. Smolek, I. Leobner, B. Heinzl, G. Gourlis, K. Ponweiser, A method for real-time aggregation of a product footprint during manufacturing, J. Sustain. Dev. Energy Water Environ. Syst. 4 (2016) 360–378.

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Parametric Optimization and Decision Support Model Framework for Life Cycle Cost Analysis and Life Cycle Assessment of Flexible Industrial Building Structures Integrating Production Planning

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Abstract: Most industrial buildings have a very short lifespan due to frequently changing production processes. The load-bearing structure severely limits the flexibility of industrial buildings and is a major contributor to their costs, carbon footprint and waste. This paper presents a parametric optimization and decision support (POD) model framework that enables automated structural analysis and simultaneous calculation of life cycle cost (LCC), life cycle assessment (LCA), recycling potential and flexibility assessment. A method for integrating production planning into early structural design extends the framework to consider the impact of changing production processes on the footprint of building structures already at an early design stage. With the introduction of a novel grading system, design teams can quickly compare the performance of different building variants to improve decision making. The POD model framework is tested by means of a variant study on a pilot project from a food and hygiene production facility. The results demonstrate the effectiveness of the framework for identifying potential economic and environmental savings, specifying alternative building materials, and finding low-impact industrial structures and enclosure variants. When comparing the examined building variants, significant differences in the LCC (63%), global warming potential (62%) and flexibility (55%) of the structural designs were identified. In future research, a multi-objective optimization algorithm will be implemented to automate the design search and thus improve the decision-making process.

Keywords: decision-making support; life cycle assessment; life cycle cost analysis; flexibility assessment; parametric performance-based design; integrated design; industrial building design

1. Introduction

The construction industry is one of the key sectors for sustainable development, as buildings account for 30 to 40% of the primary energy use worldwide [1]. Industrial businesses are facing increased pressure due to their environmental impacts [2]. Therefore, industrial buildings produce many resources and waste [3], as they consume a huge amount of materials for foundations, load-bearing structures and the building envelope [4]. The employed building materials account for the highest percentage of the total embodied energy and carbon in industrial buildings [5]. The embodied energy, which is the energy associated to the manufacturing and replacement of materials and components, is directly influenced by the service life of the building materials as well as the building life cycle [6]. Due to short product life cycles, industrial buildings have a relatively short service life, ranging from 15 to 30 years. In order to extend the life cycle of industrial buildings, building structures must be able to adapt to reconfiguring and expanding production processes, which is a challenge for structural design. Optimizing the load-bearing structure

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for flexibility and coupling of production planning models already in the early design stage can contribute to increase the economic and environmental sustainability of industrial buildings [7,8]. Nonetheless, often, structural design decisions enter the industrial building design process late and are subservient to architectural and production goals.

Flexibility can improve the sustainability of production processes [9] and building designs [10] as well as the economic performance of production facilities [11]. Yet, in the design of production facilities, architectural and engineering systems seldom respect flexibility [12], and the building is usually aligned around the production requirements and cannot react quickly to changes [13]. Moreover, the integration of sustainability dimensions and industrial building information within factory planning processes is challenging due to a sequential planning process, non-transparent information, complex discipline-specific parameter dependencies and unclear sustainability aspects [14,15]. In particular, there is a lack of understanding of the overlapping impact of changing production processes on the life cycle footprint and flexibility of the load-bearing structure of industrial buildings.

Various studies intend to formulate an integrated factory planning approach [14–18]; however, they do not examine the coupling possibility of the structural building and production process systems in an integrated industrial building model and do not integrate a method for sustainability and flexibility assessment of industrial building structures. Decision support tools for sustainable buildings should enable both life cycle cost (LCC) and life cycle assessment (LCA) calculations to compare building variants and optimize material inputs. A number of researchers perform either LCA to evaluate the environmental impact [5,19–21] or calculate LCC to determine the economic impact of industrial buildings [22–24]. There are a small number of research articles in the literature on parallel LCA and LCC analyses of industrial buildings; however, they exclusively investigate the environmental and economic impact of certain industrial building elements or components, such as façade systems [25] or insulation values, envelope construction types, skylight and solar collector coverage [26]. The cited works are not addressing the question of how to reconcile economic and environmental sustainability with the flexibility of industrial building structures and do not integrate production planning processes. The limited amount of research on flexibility in industrial buildings addresses the adaptive re-use of office and industrial buildings for residential purposes [27] and the flexible design of food processing [28] and biopharma facilities [29], or presents design guidance to support flexibility within architectural and engineering systems of factories [12]. Another study defines a categorized parameter catalogue as a design guideline for flexible industrial buildings that integrates production planning parameters [8]. However, the research conducted by Marjaba and Chidiac [30] has shown that there are no consistent metrics for evaluating the resilience and hence flexibility of industrial buildings in combination with sustainability.

The above facts highlight that the integration of structural design and production planning to increase the flexibility of industrial buildings, as well as the joint consideration of economic and environmental sustainability while evaluating flexibility, are important but still relatively unexplored topics in industrial building research. In fact, an integrated decision support framework that optimizes building structures and layouts towards improved sustainability and flexibility while taking into account production layout scenarios is lacking. Parametric modeling and performance-based design tools offer a potential way of integrating life cycle assessment optimization [31], interdisciplinary collaboration [32] and generation, and evaluation and comparison of multiple variants at an early design stage [33,34]. Therefore, the goal of this study is to establish a parametric structural optimization and decision support (POD) model framework for the LCC, LCA, and flexibility assessment of industrial buildings incorporating production planning. The main objective is to improve resource efficiency and extend the service life of industrial buildings by enabling rapid structural analysis, variant studies and decision support at an early design stage.

This paper presents ongoing research within the funded research project BIMFlexi. The main objective of the project is to create flexible and sustainable industrial buildings at an early design stage by coupling building and production planning processes and creating a holistic optimization and decision support platform for integrated industrial building design [35]. In previous research, the authors have already presented a parametric design process for structural optimization and flexibility assessment of industrial building structures [36] as well as a parametric framework for automated generation and optimization of production layout scenarios with the potential to be integrated in the parametric structural design process [37]. The research presented in this paper builds on the results of the research conducted in [8,36,37] and couples the models into the POD model framework for flexible andsustainable integrated industrial building design.

The combination of the two proposed models supports the parametric design and automated structural analysis of industrial building variants with flexibility assessment, respecting dynamic production processes; however, there is a lack of environmental and economic impact assessment to gain knowledge about the resource efficiency of the building. Therefore, a method for the simultaneous LCC, LCA and recycling potential assessment of building structures is developed and implemented. A novel rating system that allows design teams to quickly compare the performance of different building variants complements the framework. Hence, the POD model framework is designed as a set of interacting subsystems:

- Requirement specification and component library of industrial building elements and economic and environmental indicators, enabling the POD model generation and LCC, LCA and recycling potential assessment.
- Production model integrating parametric production layout scenarios [37] as geometry and load requirements and constraints for the POD model.
- POD model: Parametric structural design process generator [36] enabling (1) automated generation of the parametric geometry, structural model and loads, (2) automated application of the geometry and load requirements from the imported production layout scenarios to the structure, (3) building variant generation, (4) automated structural analysis and dimensioning of the structural elements, and (5) automated performance assessment of LCC, LCA, recycling potential and flexibility.
- Variant visualization and grading: The integration of a novel grading system enables the performance comparison of the generated building variants, thus facilitating decision making.

The developed framework is tested on a pilot-project of a food and hygiene production facility to evaluate the framework and validate the calculation results. It is evaluated whether the application of the framework enables an adequate performance assessment and offers the possibility to identify potential savings in terms of economic and environmental resource efficiency at the significant early design stage.

2. Literature Review

The main purpose of this study is to establish a framework for automated structural analysis of industrial buildings with simultaneous LCC, LCA, recycling potential and flexibility assessment, incorporating production layout planning to improve resource efficiency and extend the service life of industrial buildings at an early design stage.

Various researchers assess the LCA and/or LCC of industrial buildings. Rodrigues et al. [5] evaluated the embodied carbon and energy of an industrial building using a gate-to-gate LCA method. The results showed that the building materials are the main contributors to the environmental impact, with a total embodied carbon of 508.57 $kgCO_2eq/m^2$ and a total embodied energy of 4908.68 MJ/m^2. Marrero et al. [38] presented a methodology for environmental evaluation of industrial building projects in Spain. They selected carbon footprint and water footprint as environmental indicators and conducted a comparative analysis. Concrete and cement, along with metals and aggregates, control the carbon footprint impact in the structure but also in the roof and fixtures. The results revealed the high recycling potential of industrial buildings, especially from concrete and cement, suggesting that the evaluation of the buildings life cycle and recycling potential should be included in future studies, since industrial buildings have a short life span. Opher et al. [19] conducted a life-cycle greenhouse gas emission assessment of an industrial building restoration in Canada. The analysis included a cradle-to-grave LCA of construction materials, transport, and construction activities for the restoration process, as well as the future operational energy use. The authors highlighted that among the biggest uncertainties in the analysis are the useful service life of new technologies and the building itself, as well as the specifics of future building materials and activities. The results showed that the overall embodied carbon is sensitive to changes in the building's lifetime, material transport distances and recyclable steel components. It has been noted that alternative modeling decisions of certain materials or components can lead to results that differ by more than 15%. Therefore, 69% percent of the carbon comes from the materials used in the construction system. Bonamente and Cotana [20] conducted a systematic cradle-to-grave LCA of four prefabricated industrial buildings in Italy considering carbon and primary energy footprint on a 20 and 50-year lifetime. The analysis served to setup a parameterized model that assists to study the impacts of industrial prefabricated industrial buildings over the input parameter space. The results revealed that the carbon footprint is sensitive to the building lifetime. For a 10,000 m^2 building, the carbon footprint is 2608 $kgCO_2eq/m^3/year$ for a 20-year lifetime and 3516 $kgCO_2eq/m^3/year$ for a 50-year lifetime. The average carbon footprint of the four selected buildings, considering a 50-year lifetime, high-energy performance and deep foundations, is 133.7 $kgCO_2eq/m^3$ and 33.95 $kgCO_2eq/m^3$, when not considering the use phase. Tulevech et al. [21] performed an LCA on a low-energy industrial building located in Thailand on a 20-year lifetime, carrying out a multi-scenario analysis that revealed significant energy-saving potential through recycling strategies and a rooftop PV system. They state that the material manufacturing phase bears the largest impact on the primary energy demand (71%) and the global warming potential (60%), largely due to steel and concrete production and a higher embodied energy quantity per material.

Besides the significance of the environmental impact of industrial buildings, they also consume a considerable amount of money for the cost of execution of the building, cost of materials and supplies and maintenance and demolition, which is relevant for the economic sustainability [3]. Li et al. [22] conduced a life cycle cost analysis of non-residential green buildings (commercial buildings, industrial buildings and institutional buildings) in a tropical climate by comparing the LCC, Construction Costs (CC) and Operation Costs (OC). The results revealed that the annual LCC and CC of industrial buildings, including factory and office building and transportation, are the highest among the three examined building types, while the annual OC of industrial buildings is identified as the lowest among the three types. Weerasinghe et al. [24] presented a comparative LCC study on green and traditional industrial buildings in Sri Lanka. The results revealed that the initial construction cost of a green industrial building is 29% higher than that of a traditional building; however, in terms of LCC, green industrial buildings are 17% cheaper than the traditional buildings. Kovacic et al. [25] developed a decision support tool for evaluating the economic and environmental impact of industrial buildings' façade systems. The tool is tested by analyzing three different façade systems (steel liner tray, steel sandwich panels, cross laminated timber panels), highlighting that the initial costs of the façade systems are differing up to 27%, while after 35 years the LCC are differing by just 6%. The cross-laminated timber façade has the highest initial costs, but the best performance (80% less emissions) in terms of the Global Warming Potential (GWP). Lee et al. [26] investigated the energy performance, environmental impact, and cost effectiveness of an industrial building in Amsterdam through a full factorial design space exploration approach that supports multi-criteria decision making. Analyzed design parameters are the insulation values, envelope construction types (steel or concrete), skylight coverage and transpired solar collector coverage.

The above-presented research makes a significant contribution to knowledge about the environmental or economic impact of industrial buildings, yet it does often only analyze already planned or existing buildings, is focused on component-specific analyses or considers LCA and LCC separately. In addition, these studies do not address the linkage of structural analysis with life cycle analysis and do not intend to find structural design alternatives in correlation with production processes.

Various studies specifically deal with structural analysis and parallel LCA and/or LCC assessment. Oti and Tizani [39] presented a Building Information Modeling (BIM)-based framework for evaluating LCC, carbon and ecological footprint to assist structural engineers in assessing the sustainability of alternative design solutions at an early design stage, which currently addresses structural steel framing systems. The modeling framework employs the principles of feature-based modeling and a prototype system is implemented using NET, which is linked to a structural BIM software. Sanchez et al. [40] focused on structural analysis in terms of environmental impacts and building cost assessment, evaluating the adaptive reuse buildings, using a BIM model and different existing LCA report tools. This study demonstrates that the biggest benefits of the adaptive reuse of an existing building are in the structure. A considerable cost saving for the adaptive reuse scenario of up to 70% reduction of the structural systems construction cost was identified. Concrete was identified as the main source of environmental impact, with 56% of the total primary energy demand in the life cycle of existing structures. The reuse of steel is the main source of avoided environmental impact when recycled. Raposo et al. [41] developed a structural BIM-based LCA assessment method for seismic reinforcement of precast reinforced concrete in industrial buildings to evaluate and compare the environmental impacts of new construction and seismic reinforcement solutions in an existing building. First, analyzing the respective seismic reinforcement solution took place, then accomplishing the corresponding LCA and finally calculating the LCC for each case. Vilutiene et al. [42] developed an early-design-stage decision model to assess the sustainability of alternative load-bearing structures, using a BIM-based structural analysis tool, structural BIM software, and two extra pieces of software for cost estimation and LCA calculation. Three types of load-bearing structures for a commercial building have been compared concerning different physical parameters—cost of construction and materials, technological dimensions, and environmental impact. The authors identified the major limitation in the study as data loss during the transfer of data from one software package to another, due to the low interoperability of the different software packages, and called for integrated tools for structural designers to assess the environmental and economic impacts.

The research presented above on the assessment of environmental and economic impacts in structural design shows that LCC and LCA are usually not directly integrated into BIM and structural design tools and, therefore, multiple software applications need to be used. This requires manual data manipulation, which is time consuming and error prone and can lead to loss of data and information. Furthermore, BIM models are often not yet available in an early design stage and these toolchains are not flexible in their application for early rapid variant studies. Parametric performance-based design tools offer a potential way for early integration and variant studies. Hens et al. [43] presented a parametric framework for early-stage tall structural mass timber design to compare geometries with respect to embodied carbon of a post-beam-panel system and a post-and-platform system. The framework enables one to alter the geometry and track the impact on the embodied carbon, consisting of a parametric model in Grasshopper for Rhino3D, the plug-in Karamba3D for structural analysis, a python code for the structural design and a design space exploration component for the sampling of the design space [44]. The results showed that for both structural systems studied, building height and envelope area are good predictors and determinants of embodied carbon. Apellániz et al. [45] developed a parametric approach for early-stage building design and structural optimization, combining the environmental database of One Click LCA with a user-friendly interface and an object-oriented structure to provide parametric LCA with Grasshopper for Rhino3D. Bombyx is developed as a parametric LCA tool plug-in for Grasshopper for early building design in the Swiss context [33]; however, it lacks a method for parallel structural analysis.

Based on the presented literature review on environmental and economic impact assessment of industrial buildings and structural design processes with LCC and/or LCA performance feedback, there remain some research gaps for sustainable and flexible industrial building design. A decision support framework that optimizes building structures and layouts towards increased sustainability and flexibility while taking into account production layout scenarios is lacking. Given the increasing potential of parametric and performance-based design tools for the coupling of discipline-specific systems, it is imperative to explore the possibilities of integrating production planning and LCC, LCA, recycling potential and flexibility assessment directly into a parametric structural industrial building design process to enable rapid variant studies for decision support at an early design stage. In Reisinger et al. [36], the authors have already developed a parametric model for automated structural analysis and flexibility assessment of industrial buildings. In addition, to be able to consider changing production requirements on the building structure, a parametric framework for the multi-objective optimization of production layout scenarios, integrating flexibility and building criteria, has been developed [37]. The combination of the two proposed models into an evolved POD model framework for the automated assessment of the LCC, LCA, recycling potential and flexibility of industrial building structures, considering production layout planning, is the focus of this paper.

3. Methodology and Research Design

This paper presents the development of the POD model framework for automated integrated production planning and structural industrial building design, enabling performance feedback and visualization of the trade-off among LCC, LCA, recycling potential and flexibility assessment already at an early design stage. The framework is tested within a variant study on a real pilot-project from the food and hygiene production, evaluating the efficiency of the framework to identify potential savings in economic and environmental impacts of industrial building structures and validating the trade-off results. Figure 1 gives an overview of the research design and the scope of the paper.

This study builds upon previous research in which two novel parametric design and optimization models for integrated industrial building design were developed as described before. In this study, the parametric production layout model is coupled to the structural design model through parametric modeling in Grasshopper for Rhino3D [46]. The integrated parametric production layout scenarios [37] serve as geometry and load constraints for building design. The computational framework of the POD model consists of a parametric model constructed in Grasshopper, which is based on the design space representation presented in [36]. The parametric model is supplemented by Karamba3D components [47] for the structural analysis and automated dimensioning of the structural elements. An industrial building component library and a component-related repository are developed, storing the relevant indicators for LCC, LCA and recycling potential assessment. The statistical cost indicators for the calculation of the LCC were acquired from the German construction cost indices—BKI [48]. The indicator data for the assessment of the embodied energy and the recycling potential were obtained from the Austrian database baubook.at [49]. The repository is coupled to the parametric model to enable the automated LCC, LCA and recycling potential performance assessment of the building structure in the parametric environment. The implemented LCC is based on the calculation of the net present value (NPV) according to ISO 15686-5 [50]. The LCA is carried out for the indicators as used by IBO [51]: Global Warming Potential (GWP), expressed in CO_2 equivalent (CO_2equ.); Acidification Potential (AP), expressed in SO_2 equivalent (SO_2equ.); and Primary Energy Non-Renewable (PENRT) and Primary Energy Renewable (PERT), both expressed in MJ. In addition, the recycling potential was calculated according to the Austrian guideline to calculate the disposal indicator of building components by IBO [52]. For the visualization of the generated production layouts, building structures and performance results serve Rhinoceros 7 [53]. The building variants and performance results are visualized within a novel grading system for ranking and comparison of the building variants. The implemented grading system serves as a decision-making aid when finding the best variant from the different trade-offs of LCC, LCA, recycling potential and flexibility and is based on the method used in the DGNB system [54]. The DGNB system is a holistic certification, to make the quality of sustainable construction measurable and assessable and to serve as a planning and optimization tool for evaluating sustainable buildings.

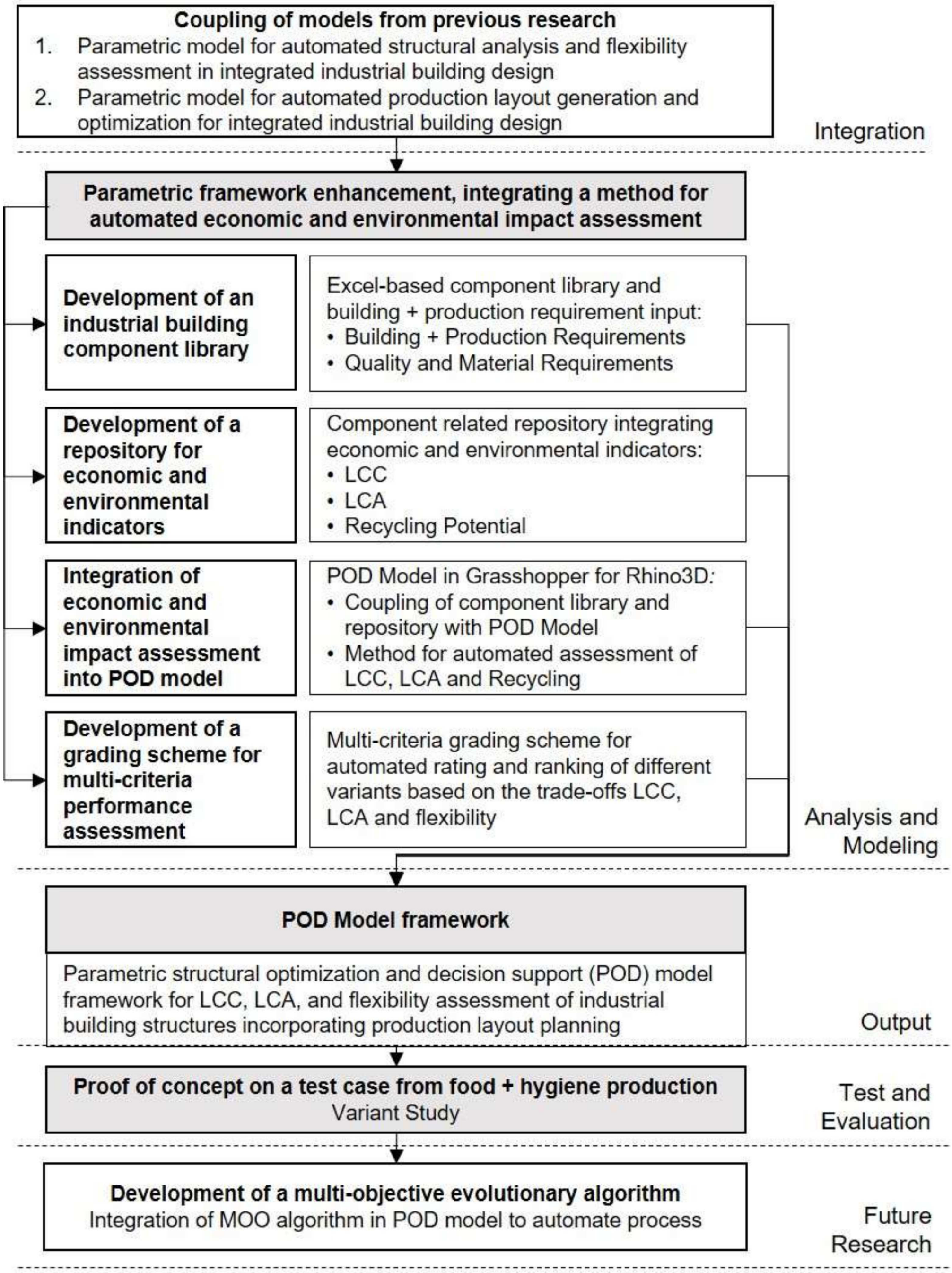

Figure 1. Overview of the research design and the scope of the paper.

Using a real test case from food and hygiene production, a proof of concept is carried out by means of a variant study. The goal is to compare the initial building design with several generic designs to validate the calculation results and to evaluate the POD model framework as a decision support tool to identify economic and environmental saving potentials. In future research, a multi-objective optimization algorithm will be developed and integrated into the framework to automate the design process and design search.

4. POD Model Framework

In this section, the developed POD model framework is presented. The framework serves as a comparative decision support tool for rapid calculation, assessment and comparison of different structural industrial building variants with feedback to LCC, LCA, recycling potential and flexibility, integrating production planning requirements. Figure 2 presents the POD model framework, which is based on five essential subsystems: (1) the discipline-specific data and production planning model specification, (2) the industrial building component library, (3) a repository of the economic and environmental indicators, (4) the POD model for automated structural analysis and performance assessment of LCC, LCA, recycling potential and flexibility, and (5) the result visualization and grading system for decision support.

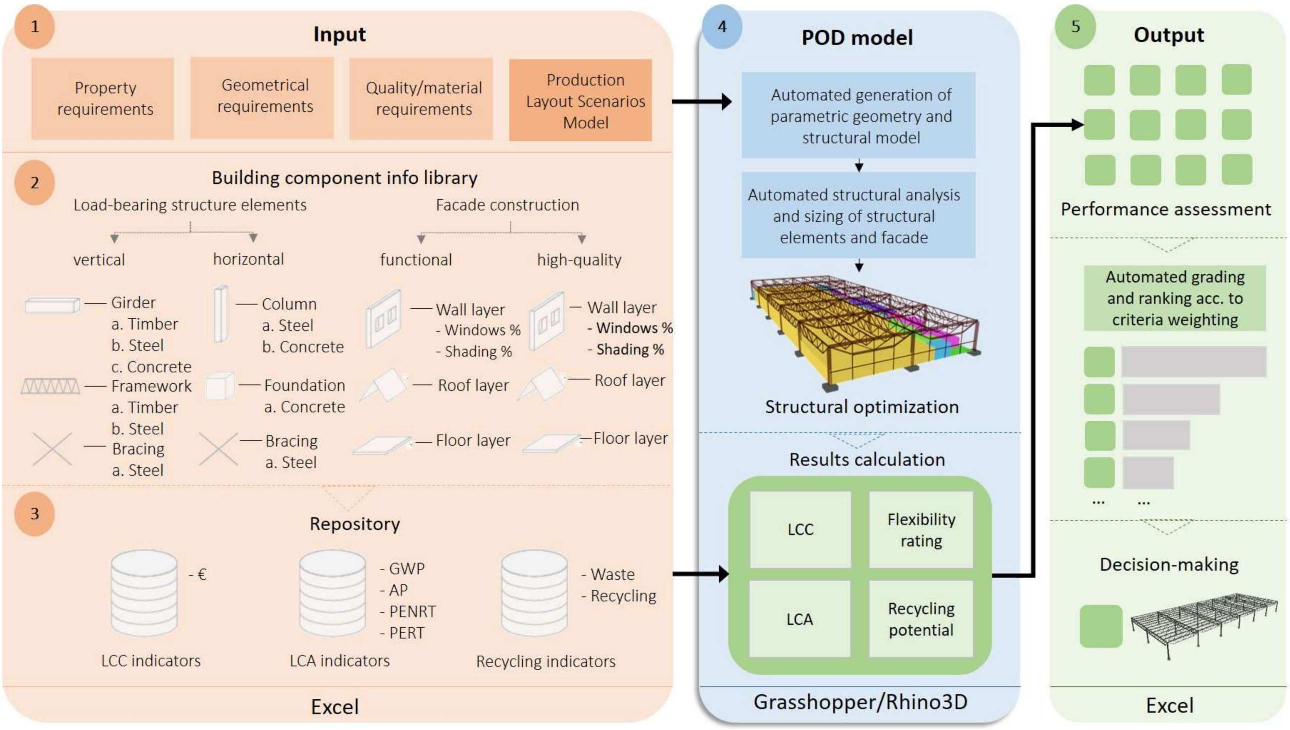

Figure 2. The POD model framework.

The POD model is developed in the visual programming tool Grasshopper for Rhino3D [46] and enables the automated structural analysis and pre-dimensioning of structural elements with Karamba3D [47]. An excel-based requirement specification is bi-directionally coupled to the POD model that enables project- (building and production requirements) and user-specific (quality and material requirements) parameter definition and includes the industrial building component library and the indicator repository for LCC, LCA and recycling potential assessment. The parametric production layout scenarios are integrated into the POD model and provide geometry and load requirements and constraints for the structural analysis. The design space and variables of the structural model are described in detail in [36] and cover the horizontal and vertical modularity and axis grid, the load-bearing structure type in the primary and secondary direction (timber, concrete and steel frameworks and girder), the column type (concrete or steel), the bracing type and the load case for retrofitting loads. Furthermore, the POD model includes the LCC, LCA and recycling potential assessment of the enclosure construction systems of wall, roof and floor layers and the window openings of the industrial hall.

Once the variable parameters are selected for a specific building variant, the parametric model automatically creates a three-dimensional structural layout, models the enclosure systems, performs the structural analysis, and determines the appropriate component sizes for each structural element and the area of the enclosure system. The parametric model reformulates the structural layout, analysis, and design when the parameter or variable values are changed. Based on the determined structural component sizes and enclosure system areas, the masses of the materials are calculated. The LCC, LCA, and recycling potential assessment is then determined by multiplying the material masses and areas with the appropriate indicators from the indicator repository. The evaluation of flexibility is directly integrated into the parametric design process and depends on the layout design, dimensions and load-bearing capacity of the structure. For the visualization of the production layouts, building structures and performance results serves Rhino3D [53]. The generated building variants and assessment results are visualized in the grading system for performance ranking and comparison of the building variants. The grading system serves as a decision-making aid when finding the environmental and economic best-performing building variants in terms of LCC, LCA, recycling potential and flexibility assessment.

Figure 3 gives a more detailed explanation of the data and model integration in the POD model framework and presents the framework for integrated industrial building design to enable flexible structural and production layout planning.

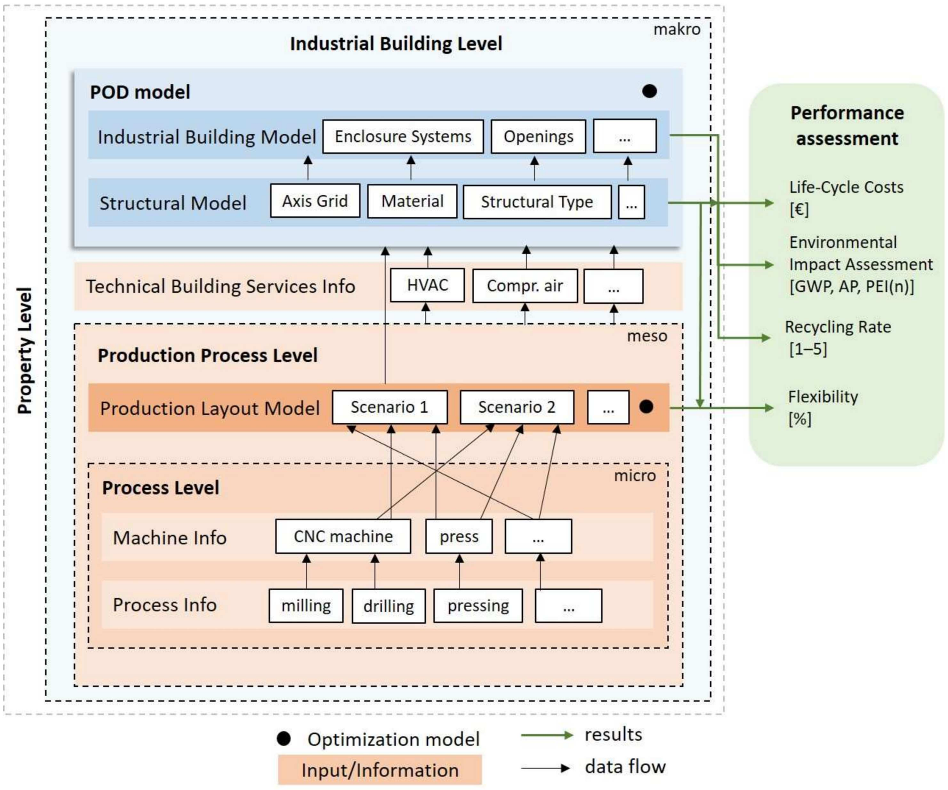

Figure 3. Framework for integrated industrial building design to enable flexible structural and production layout planning.

The integrated industrial building framework is structured on three levels: micro, meso and macro. In the micro level, the process of the production system is described and gives information on necessary machines and processes. The information of the micro level flows into the meso level, the production process level. The production process level is represented by the parametric evolutionary optimization model for automated production layout planning [37], providing multiple production layout scenarios to be respected in the structural building design process. The technical building service information relates to the media flow and is dependent on the production process, integrating building-service-related information, such as load distribution, geometry and space requirements for media supply into the structural design process. The macro level is referred to the industrial building level and contains the POD model. The production planning and related technical building service parameter serve as information for the POD model. The POD model automatically analyzes, dimensions the structural system, and then assesses the performance in terms of the LCC, LCA, recycling rate and flexibility of the building.

4.1. *Objectives for Performance Assessment Integrated in the POD Model*

The goal of integrating LCC, LCA, recycling potential and flexibility assessment into the early structural design process is to provide a methodology for minimizing the material consumption and to compare the economic and environmental impact of different design variants, streamlining the decision-making process towards increased sustainability and durability. Figure 4 presents the set of objectives respected in the POD model framework for performance evaluation of the industrial building structures. On the one hand, the costs and environmental emissions should be reduced; on the other hand, the flexibility of the industrial building structure should be maximized. The economic objective is the (O1) minimization of the LCC. The environmental objectives consider the minimization of the (O2) GWP, (O3) AP, (O4) PEI and the (O5) PERT. The objective (O6) recycling potential should be maximized. The pursued flexibility objectives are (O7) the maximization of the load-bearing capacity for retrofitting, (O8) maximization of the expandability of the production layout, (O9) maximization of the hall height reserve and (O10) minimization of the number of columns standing inside the production area.

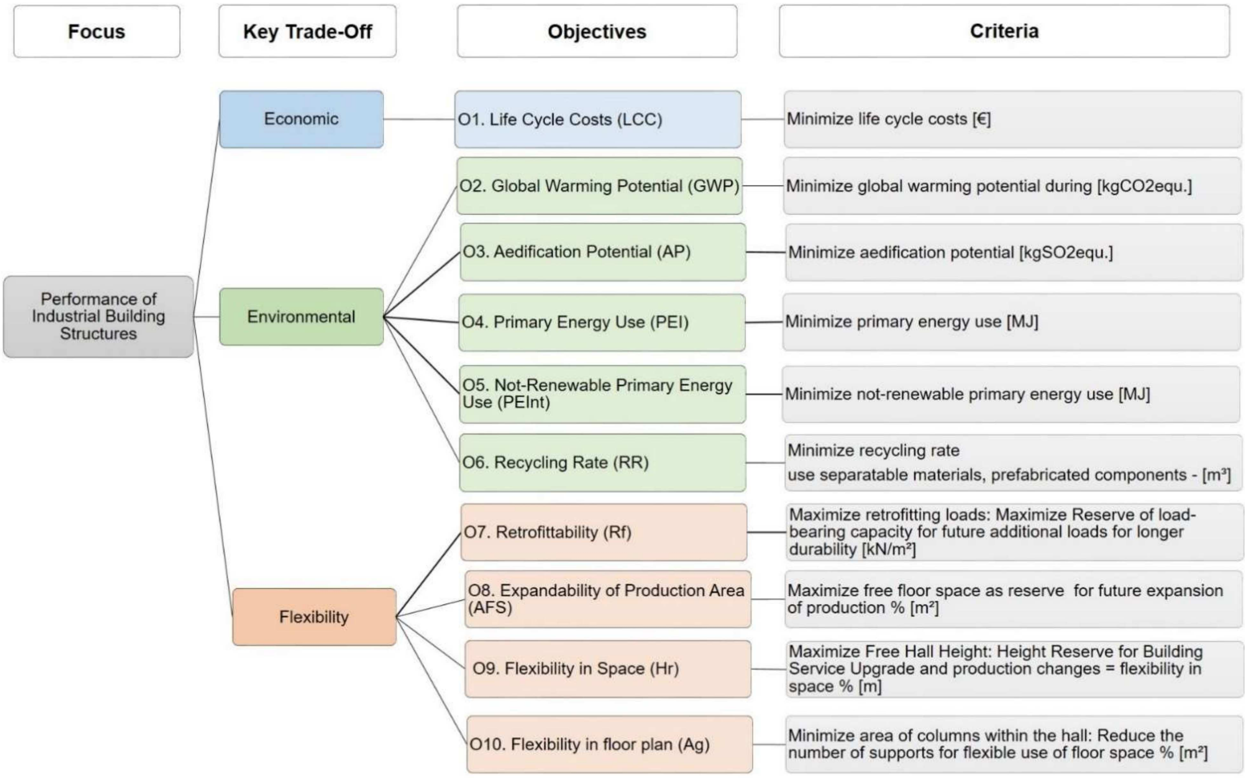

Figure 4. Key trade-offs and related objectives included in the POD model framework for performance assessment of industrial building structures.

4.1.1. Life Cycle Cost Analysis

In order to calculate the indicator of O1, the NPV is used to determine the LCC of the load-bearing structure and enclosure systems. The NPV is a common measure used in LCC analysis, where C is the cost in year n, q the discount factor, d the expected real discount year p.a., n is the years between the base date and occurrence of cost and p is the period of analysis (see Equation (1)) [50]:

$$\text{LCC (NPV)} = \sum(Cn \times q) = \sum_{n=1}^{p} \frac{C_n}{(1+d)^n} \tag{1}$$

4.1.2. Life Cycle Assessment and Recycling Potential Calculation

The LCA quantifies the environmental impacts of the embodied energy of the load-bearing structure and enclosure systems. The chosen functional unit is 1 m^2 per gross floor area (GFA) as the most common unit in building and construction studies. The LCA is carried out according to IBO [51] for the life cycle stages production and maintenance to identify the embodied energy of the load-bearing structure (primary and secondary structure, columns, bracing and foundation) and the enclosure construction (wall, roof and floor construction layers). The indicators for the assessment of the embodied energy, obtained from the Austrian database baubook [49], is implemented in the component related indicator repository. The phases of production (manufacturing of materials) and maintenance (replacement of materials or elements after the end of service life) are considered. The environmental impact of the transport of the materials from the extraction area to the manufacturer is included; transport from the manufacturer to the construction site is not part of the assessment.

The recycling potential indicates the percentage of material amount, which is recyclable and which is disposed of as waste and is calculated according to IBO [52].

4.1.3. Flexibility Assessment

The definition and mathematical formulation of the considered flexibility metrics are presented in Reisinger et al. [36], enabling the quantitative flexibility assessment of the industrial building structures. We define flexibility “as the ability of the building structure to resist and adapt to changes in use through changing manufacturing conditions”. Hence, the POD model rates the flexibility of the building structure and layout according to the four flexibility metrics of Retrofittability, Expandability, Flexibility in space and Flexibility in floor plan.

4.2. Grading System for Performance Comparison of Different Building Variants

A novel grading system is developed to make the performance of building variants rapidly comparable and the best variants visible. The performance assessment results of each generated building variant from the POD model are visualized in the grading system. The grading system rates the performance factors of each building variant regarding the LCC, LCA, recycling potential and flexibility result. Each performance factor is graded according to the grading scheme presented in Figure 5. Applying a grading scale from 1 (excellent) to 5 (failure) allows the design team to compare the different variants and trade-offs efficiently. Since the individual eco-indicators of the LCA (GWP, AP, PENRT and PERT) have different significance on the overall ecological building performance, they are weighted with significance factors to determine one weighted LCA environmental impact value according to the DGNB system [54]. It is difficult to find single optimal solutions in multi-criteria optimization studies when not assigning weights to the evaluation objectives [55]. Therefore, the framework allows the decision maker to assign relative weightings to the performance factors, enabling the design team to give preferences in the design search.

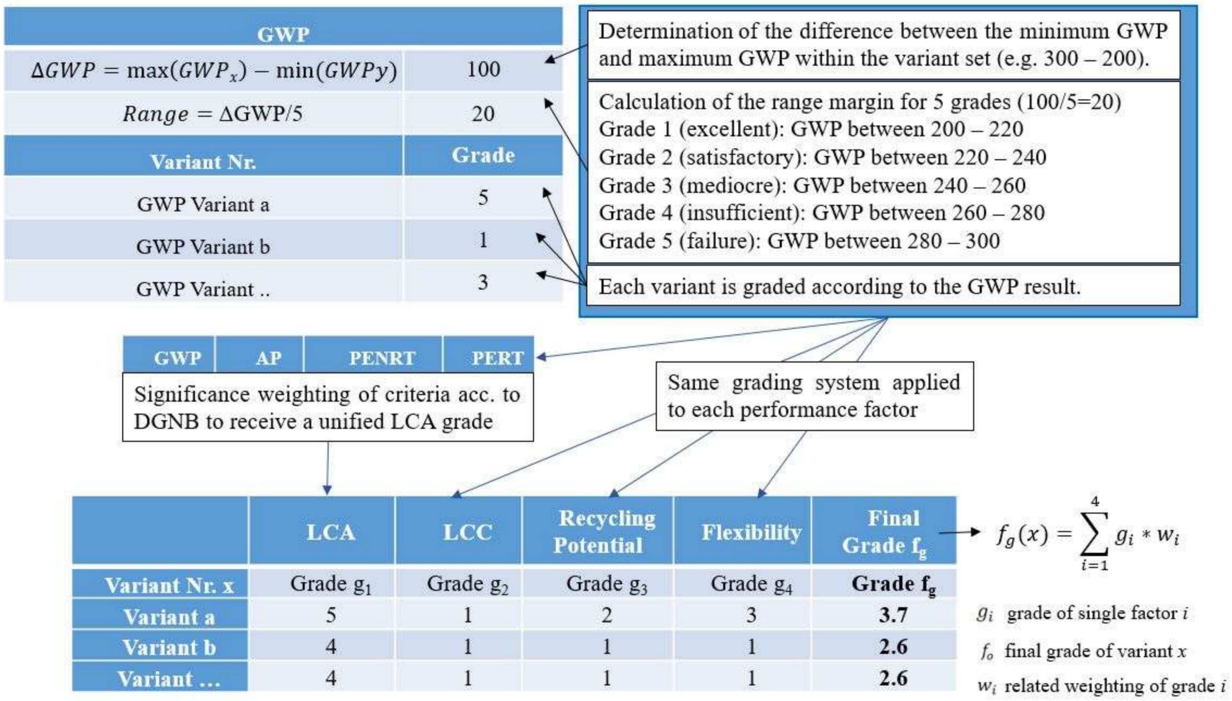

Figure 5. Grading methodology to make the performance of building variants rapidly comparable.

5. Test Case

This section presents the conducted test case and the performed analysis to demonstrate the suitability of the POD model framework as a decision support tool and to validate the implemented objectives in the performance assessment. The test also aims to evaluate the efficiency of the framework to quickly support the identification of environmental and economic saving potentials in an industrial building variant study at an early design stage. The proposed framework is tested on a real food and hygiene production facility located in Austria, which was chosen because of the high density of available information and data. The examined industrial building is a production hall of a food and hygiene manufacturer with outer building dimensions of 120 m × 48 m, resulting in a GFA of 5760 m^2. It consists of one functional production floor, where the manufacturing system with the machinery and stock of materials is placed. The production hall has a building height of 20 m, configuring a gross building volume of 115,200 m^3. The load-bearing structure consists of precast concrete columns (60 cm × 60 cm) and the roof structure consists of steel frameworks with span widths of 12 m as in the primary direction and 24 m in the secondary direction. The floor of the production hall is a monolithic floor slab and the façade is made of vertically laid sheet metal panels with a total thickness of 12.0 cm. The roof covering consists of a trapezoidal sheet metal roof construction.

5.1. Variant Study Structure

A variant study is carried out in order to test the POD model framework. The goal is to compare the initial industrial building design from the test case with several generic design variants to validate the calculation results and to evaluate the POD model framework's potential as a decision support tool to identify savings by means of economic and environmental impacts.

The property, production program and geometrical requirements of the test case are used as a consistent parameter for the POD model. In total, twelve structural and three enclosure construction variants are investigated. In the study, the real use case is compared to these twelve building variants, which vary in axis grid dimensions, primary and secondary structure type and the applied enclosure system. The structure of the variant study and the examined combinations of structural and enclosure systems are shown in Table 1. Table 2 presents the construction layers of the considered enclosure system variations. The POD model considers window and shading areas in the façade and roof structure as a percentage of the area occupied. In the test case, it is assumed that the building has a window area ratio of 20%. For the LCC calculation, a general price increase of 2% and an expected real discount of 5% are assumed.

Table 1. Variant study design: examined structural types and envelope combinations.

Variant	Axis Grid (m)	Primary Structure	Secondary Structure	Column Type	Enclosure
0 Real case	24 × 12	Steel framework	Steel framework	Precast concrete	Real case
1 C_flex	16 × 12	T-girder concrete	Concrete girder	Precast concrete	High quality
2 SF_flex	24 × 20	Steel framework	Steel framework	Precast concrete	High quality
3 SP_flex	12 × 20	Steel profile	Steel profile	Precast concrete	High quality
4 TG_flex	12 × 12	Timber girder	Timber girder	Precast concrete	High quality
5 TF_flex	12 × 12	Timber framework	Timber framework	Precast concrete	High quality
6 SM_flex	24 × 20	Steel framework	Steel profile	Precast concrete	High quality
7 C_cost	12 × 6	T-girder concrete	Concrete girder	Precast concrete	Functional
8 SF_cost	12 × 12	Steel framework	Steel framework	Precast concrete	Functional
9 SP_cost	12 × 6	Steel profile	Steel profile	Precast concrete	Functional
10 TG_cost	12 × 6	Timber girder	Timber girder	Precast concrete	Functional
11 TF_cost	12 × 6	Timber framework	Timber framework	Precast concrete	Functional
12 SM_cost	12 × 6	Steel framework	Steel profile	Precast concrete	Functional

Table 2. Layer of the examined envelope constructions: functional and high quality.

Functional Enclosure Construction		
Roof Construction	**Exterior Wall Construction**	**Floor Construction**
0.88 cm aluminum trapezoidal sheet 0.001 cm vapor barrier 20 cm mineral wool insulation 0.05 cm separating fleece PP 0.2 cm plastic roofing membrane 1 ply	0.1 cm Powder-coated aluminum 16 cm mineral wool insulation 0.1 cm powder-coated aluminum 0.5 cm joint tape	80 cm gravel fill/rolling 0.04 cm polyethylene foil 8 cm blinding layer (concrete) 25 cm reinforced concrete 0.01 cm expoxy coating
High Quality Enclosure Construction		
Roof Construction	**Exterior Wall Construction**	**Floor Construction**
0.88 cm aluminum trapezoidal sheet 0.1 cm aluminum sheet 0.001 cm vapour barrier 20 cm mineral wool insulation 0.05 cm separating fleece PP 0.2 cm plastic roofing membrane 1 ply 0.02 cm polyethylen foil 9 cm vegetation layer of hummus	30cm reinforced concrete wall 14 cm mineral wool insulation 8 cm reinforced concrete wall	80 cm gravel fill/rolling 0.04 cm polyethylene foil 8 cm blinding layer (concrete) 25 cm reinforced concrete 2 cm plastic modified screed

In this study, the two time scenarios of 25 and 50 years, typically for industrial building studies, are considered. The maintenance of the building components was included in the analysis, which means that in the scenario of 50 years many of the enclosure layers had to be replaced due to the expiration of the life duration. For the load-bearing structure elements, which usually have a life expectancy of 100 years, no maintenance had been considered according to life durations suggested in IBO [51].

Applying the POD model, the environmental and economic impacts of the structural and enclosure materials are assessed for the time scenarios of 25 and 50 years. Subsequently, three different weighting scenarios are examined (see Table 3) to discuss and compare the variant performance results: (1) equal weighting, (2) ecologic weighting and (3) economic weighting.

Table 3. Applied weighting scenarios in the variant study.

Performance Factor	EQUAL Weighting (%)	ECOLOGIC Weighting (%)	ECONOMIC Weighting (%)
LCA	25	35	10
Costs	25	10	80
Recycling	25	35	10
Flexibility	25	20	0
Σ	100	100	100

5.2. Results

In order to allow for a more accurate interpretation of the results, Tables 4 and 5 are presenting the results for the structural system and the enclosure system separately. Table 4 shows the LCC, LCA, recycling potential and the flexibility rating of the examined structural variants on the time scenario of 50 years. Table 5 presents the LCC, LCA and recycling potential results of the different building envelope variants on the time horizons of 20 and 50 years.

Table 4. LCC, LCA criteria, recycling potential and flexibility rating results of the examined structural systems of the building variants for the time scenarios 20 and 50 years.

25 and 50 Years	LCC € Million	GWP t CO_2equ.	AP t SO_2equ.	PENRT GJ	PERT GJ	Waste t	Recycling t	Flexibility Rating
0 Real case	0.80	1037.50	0.66	3484.20	797.22	463.83	648.98	0.20
1 C_flex	1.53	829.38	0.73	3637.00	974.53	1092.38	1204.89	0.26
2 SF_flex	0.96	972.77	0.58	3138.10	696.48	325.74	504.72	0.38
3 SP_flex	1.76	1465.80	0.89	4772.10	1066.70	527.69	795.57	0.18
4 TG_flex	0.78	746.42	0.70	1819.90	4724.70	743.59	993.26	0.35
5 TF_flex	0.74	858.18	0.75	2224.00	4518.80	749.95	1012.34	0.15
6 SM_flex	1.75	1396.20	0.81	4385.50	952.73	367.16	628.97	0.20
7 C_cost	1.42	1568.90	1.27	6431.10	1665.80	1686.12	1917.67	0.19
8 SF_cost	0.79	1240.80	0.83	4368.40	1033.20	725.28	938.33	0.31
9 SP_cost	1.01	1791.40	1.28	6638.50	1622.90	1328.13	1621.90	0.17
10 TG_cost	0.73	1423.60	1.15	4966.60	3550.20	1328.07	1621.70	0.32
11 TF_cost	0.65	1642.40	1.24	5818.80	2924.30	1336.80	1647.91	0.35
12 SM_cost	0.94	1939.10	1.36	7073.70	1712.40	1342.58	1665.25	0.29

Table 5. LCC, LCA and recycling potential assessment results of the examined enclosure construction variants for the time scenarios 25 and 50 years.

25 Years	LCC € Million	GWP t CO_2equ.	AP t SO_2equ.	PENRT GJ	PERT GJ	Waste t	Recycling t
Real case	2.07	1156.60	3.72	13,113.00	2982.60	4566.43	8404.49
Functional	1.87	1126.07	3.69	12,179.83	3113.98	4554.49	8620.81
High-quality	2.71	1570.28	5.02	16,463.00	5392.80	5717.48	9877.13
50 Years	**LCC € Million**	**GWP t CO_2equ.**	**AP t SO_2equ.**	**PENRT GJ**	**PERT GJ**	**Waste t**	**Recycling t**
Real case	2.43	1480.40	5.10	17,360.00	3977.60	4677.33	8464.98
Functional	2.22	1584.75	5.79	18,239.00	4652.27	4741.83	8704.40
High-quality	3.06	2135.15	7.63	22,885.67	8423.05	6089.66	10,483.48

As can be seen in Table 4, the real case is amongst the best-performing variants within all factors compared to the other variants. The best-performing variants regarding the GWP result are the timber variants TG_flex and TF_flex. However, regarding the flexibility rating, TF_flex performs better than TG_flex. This is due to the flexibility rating, as the framework restricts the flexibility in space because of higher girder construction. As expected, both timber variants show significantly high values for renewable primary energy use. For the AP indicator, the variants C_Cost, SP_cost, TF_cost and SM_cost have the highest impact. These variants work with the smallest possible axis grid of 6 m × 12 m, resulting in a higher number of concrete columns in the building. The most cost-efficient variants are TG_cost and TF_cost, which also perform well in terms of recyclable material and a high flexibility rating. Due to the large span, corresponding large cross-section dimensions and the high dead load of concrete structures, the variants C_flex and C_cost have a high impact on the amount of waste and costs. The SM_flex and SM_cost variants have a rather high influence on the GWP emissions due to their steel construction.

The results of the enclosure construction in Table 5 show that the GWP of the real case after 25 years is 1156.60 $\text{tCO}_2\text{equ/m}^2$ and after 50 years 1480.40 $\text{tCO}_2\text{equ/m}^2$. The difference between the real case and the functional enclosure construction is very small. The functional enclosure construction has a slightly smaller GWP impact after 25 years (1126.07 $\text{tCO}_2\text{equ/m}^2$) but a slightly higher GWP result after 50 years (1584.75 $\text{tCO}_2\text{equ/m}^2$) than the enclosure construction of the real case. The results of the high-quality enclosure construction show that the environmental and economic impact is higher than the other two variants. As a result, the high-quality façade made of precast concrete elements will have a negative impact on the more flexible types of structures. In terms of waste mass, it can be seen that over 1000 t/m^2 more waste is generated when applying the high-quality enclosure system due to the concrete sandwich wall panels. The higher costs of the high-quality system are primarily due to the concrete sandwich elements of the wall, but the green roof also plays a significant role.

The discussion of the results above referred to the interpretation of the individual performance factor values of the variants. However, this presentation makes it challenging for design teams to make a direct comparison between building variants and to select the most suitable option. Therefore, the criteria grading system for rating and comparison of the variants is implemented in the POD framework. The grading of the performance factors of each building variant on the time scenarios of 25 and 50 years is presented in Table 6, showing the results of both the structural and the enclosure system.

Table 6. Grading results of the LCC, LCA, recycling potential and flexibility rate of the examined building variants, respecting the impact of the structural and enclosure systems listed for the time scenarios of 25 and 50 years.

Grade	**LCC**		**LCA**		**Recycling**		**Flexibility**		**Final Grade**	
years	**25**	**50**	**25**	**50**	**25**	**50**	**25**	**50**	**25**	**50**
0 Real case	1.6	1.6	1.1	1.0	1.0	1.0	4.0	4.0	1.9	1.9
1 C_flex	4.3	4.2	3.0	3.4	5.0	5.0	3.0	3.0	3.8	3.9
2 SF_flex	3.0	3.0	2.9	3.3	3.1	3.3	1.0	1.0	2.5	2.7
3 SP_flex	4.6	4.6	4.2	4.3	3.6	3.7	5.0	5.0	4.3	4.4
4 TG_flex	2.8	2.8	2.9	3.4	4.2	4.3	1.0	1.0	2.7	2.9
5 TF_flex	2.8	2.7	3.2	3.7	4.3	4.4	5.0	5.0	3.8	4.0
6 SM_flex	5.0	5.0	4.4	4.6	3.8	3.9	4.0	4.0	4.3	4.4
7 C_cost	2.4	2.4	2.6	2.8	3.7	3.5	5.0	5.0	3.5	3.4
8 SF_cost	1.1	1.1	1.3	1.8	1.6	1.6	2.0	2.0	1.5	1.6
9 SP_cost	1.6	1.5	2.9	3.0	2.9	2.8	5.0	5.0	3.1	3.1
10 TG_cost	1.1	1.1	2.3	2.6	2.9	2.8	2.0	2.0	2.1	2.1
11 TF_cost	1.0	1.0	2.9	3.1	3.0	2.9	1.0	1.0	2.0	2.0
12 SM_cost	1.6	1.6	3.5	3.5	3.0	2.9	2.0	2.0	2.5	2.5

As can be seen in Table 6, the real case has a very good rating regarding the LCC, LCA and recycling rate. The real case is the second-best solution, with a rating of 1.9. Merely the SF_cost variant achieves a better rating with 1.5. The flexibility of the load-bearing structure of the real case is rated with 4.0 and is thus one of the less favorable variants regarding flexibility. The LCC rating of the variants SF_cost, TG_cost and TF_cost is better than the LCC rating of the real case. The _flex variants are the variants with the high-quality enclosure system applied; thus, they have a worse LCA grading than the _cost variants with a functional enclosure system. The results of the grading system table indicate that the SF_flex, TG_flex, and TF_cost are those with the best flexibility rating.

Figure 6 presents the final performance assessment results of the examined building variants on the time horizon of 25 years, comparing the results of the three weighting scenarios—equal, ecologic and economic. The performance evaluation results indicate that the real case is among the best-performing variants in each weighting scenario, with a score of 1.9 in the equal weighting, 1.7 in the ecologic weighting, and 1.5 in the economic weighting scenario. The best-rated option within the equal weighting scenario is the SF_cost variant, with a rating of 1.5. SF_cost also performs as the best variant in the economic weighting scenario (1.5) and the economic weighting scenario with (1.2).

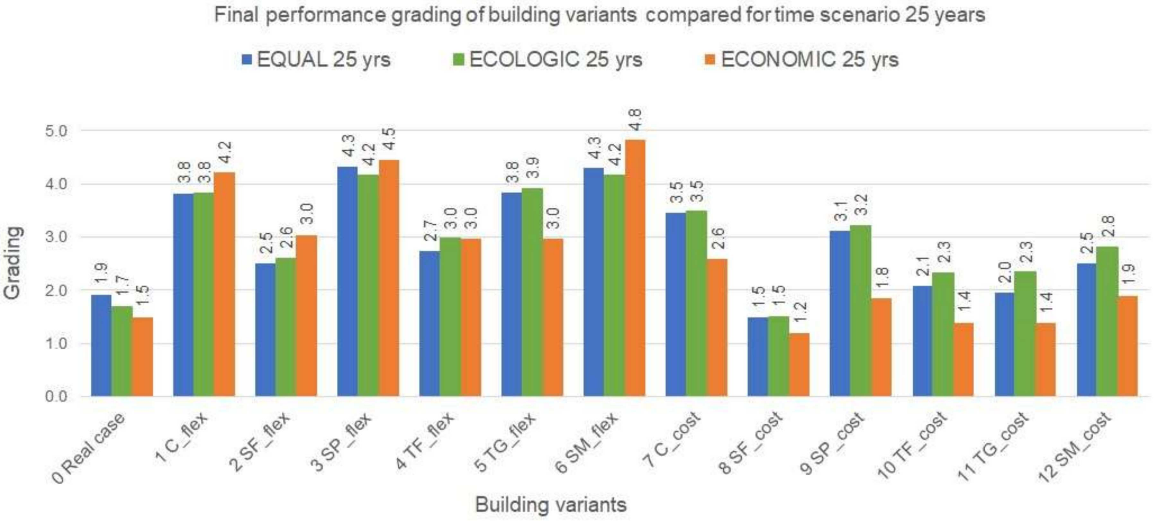

Figure 6. Final performance grading and comparison of the examined building variants for the time scenario 25 years and the weighting scenarios (equal, ecologic and economic).

Figure 7 presents the performance assessment results of the examined building variants on the time horizon of 50 years, comparing the results of the three weighting scenarios equal, ecologic and economic. After 50 years, the SF_cost variant is the best-performing building, as it was in the 25-year time scenario. In the scenario in which the focus is on the costs of the building, the variants TF_cost and TG_cost also perform very well, with a rating of 1.4. The real case and the SF_cost variants are the best-performing variants when seeking environmentally sustainable buildings. The highest economic and ecologic impact has the variant SM_flex. The decision maker would now have to decide whether the industrial building should strive for more ecology or economy.

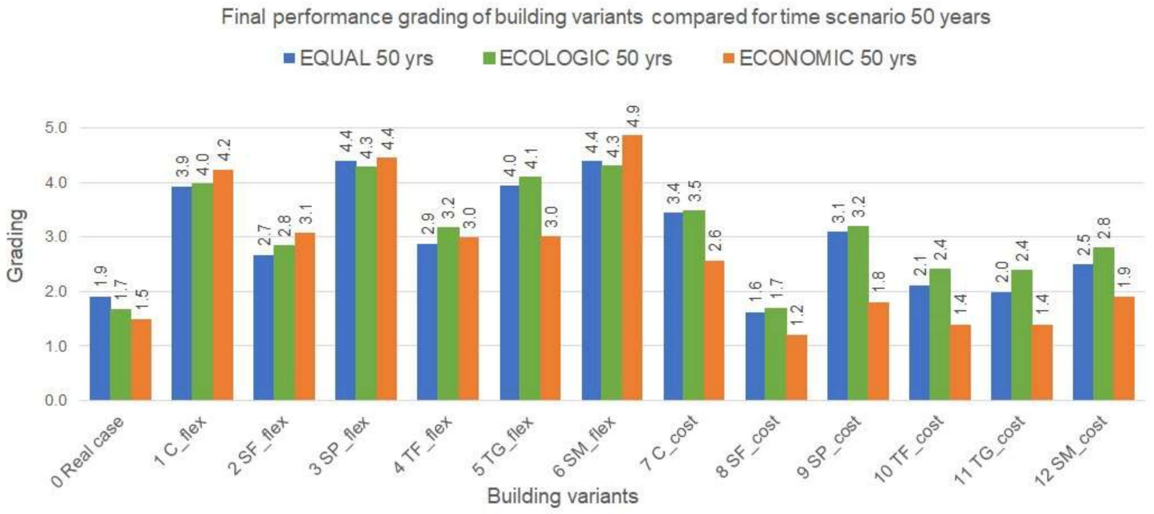

Figure 7. Final performance grading and comparison of the examined building variants for the time scenario 50 years and the weighting scenarios (equal, ecologic and economic).

6. Discussion

To improve the sustainability and flexibility of industrial buildings, a parametric optimization and decision support model framework for integrated industrial building design, coupling structural design with production planning, was presented. The presented model in Reisinger et al. [36] improves the flexibility and economic benefit of industrial building structures, while the developed POD model framework presented in this paper integrates an additional method for parallel LCC, LCA and recycling potential assessment to improve the resource efficiency of industrial buildings in long-term. The proposed framework enables the generation, analysis, and comparison of different structural industrial building variants to provide design teams with a better understanding of the environmental and economic impacts of alternative design choices such as horizontal and vertical axis grid, the load-bearing structure type, the column type, the bracing type, the load case for retrofitting loads and the enclosure system.

Variant studies and decision support tools that provide feedback on the environmental and economic performance of alternative modeling choices can help to identify potential savings in the cost and carbon footprint of industrial building elements or components [19,24,25]. The results of the test case demonstrate the effectiveness of the POD model framework for identifying potential economic and environmental savings, specifying alternative building materials, and finding low-impact industrial building structures and enclosure system variants. The results presented in Table 4 show that the LCC after 50 years can differ by up to 63% when distinguishing between the best and worst structural variants. The carbon footprint of the structural system could also be reduced by up to 62% after 50 years. Comparing the flexibility rates of the best and worst evaluated structural variants, there is a difference of 55%. Comparing the generic structural variants with the real case, it was possible to find structures that could reduce LCC by 19% and GWP by 28%. In addition, structural variants were found which would have a higher flexibility rating (+15%) than the real case.

In line with existing research on environmental performance assessment of industrial buildings [21,38,40], the study results show that more processed materials such as concrete and metal variants contribute to a higher environmental impact, as their processing involves more energy and, therefore, generates more carbon emissions. Due to the large span, corresponding large cross-section dimensions and the high dead load of the investigated concrete structures, the concrete variants have a high impact on the amount of waste and costs. On the contrary, timber constructions are generally low in carbon and perform better. The best-performing variants regarding the GWP result are the examined _flex variants that work with bigger axis grids, resulting in a decreased number of concrete columns in the building. This indicates that a higher number of supporting columns in the hall not only restricts the flexibility but also has a negative impact on the ecological performance of the buildings.

The study results reveal that the enclosure systems have a higher economic and environmental impact than the load-bearing structure due to the big surface area of the façade, roof and floor construction and thus the resulting amount of materials used. This is in line with findings in existing literature, which, therefore, suggests designing shorter and more regularly shaped buildings in terms of embodied carbon [43]. The test case shows that the structural systems with a high flexibility perform worse in the overall performance analysis, as the high-quality enclosure system was applied to the flexible structures in the variant study. The high-quality enclosure has a much greater economic and environmental impact than the functional system. A separate consideration of the structural system and the enclosure construction in decision making is suggested to identify the best combinations and to achieve flexible and sustainable building solutions. In this study, the impact of window and shading areas in the façade and roof structure was investigated by a percentage factor of 20% openings in the façade. A detailed analysis of the impact of different window and façade systems on the building performance should be investigated in future research.

The test case demonstrates that the developed framework enables the comparison of different factors affecting the embodied energy and costs of industrial building structures and enclosure systems along the life cycle. Applying the framework in practice can help prevent waste production at an early stage as the framework enables assessment of the buildings recycling potential, as suggested in literature [21,38]. However, it is important to highlight the fact that the results of this study do not include the operational stage or energy efficiency of industrial buildings as it was examined in related research [19,21,22,26] and is a topic for future research.

The presented POD model framework takes a first step towards interdisciplinary integration in industrial building design, which represents valuable contribution to current research on integrated factory planning [14–18]. In this research, we solved the problem of sequential planning processes and the lack of integrated decision support in industrial building design by pushing the structural design optimization into the early design stage, directly coupling it with production layout planning. Thus, the proposed framework offers the possibility to include changing production layout scenarios in structural design studies to increase the resource efficiency and durability of industrial buildings. In this study, only one fixed production layout scenario has been investigated. However, changing production types and requirements have a significant impact on the building performance, and constant reconfiguration of manufacturing systems demands highly flexible building structures [7]. The effect of different production layout scenarios on the building structures, using the POD model framework, will be investigated in future research.

Currently, the POD model requires manual manipulation of the design variables in the visual programming environment, which is not intuitive and can be time consuming when creating and evaluating a large number of building variants. The design space exploration in structural optimization studies can be automated [43–45]. In the next steps of the research, we aim to develop a multi-objective evolutionary optimization algorithm and integrate it into the POD model framework to automate the design process and design search. The POD model framework can be useful in providing interdisciplinary stakeholders with a better understanding of the implications of their design decisions; however, the proposed parametric approach still has limitations in terms of usability and visualization capabilities. In further research, we will develop a method to couple the POD model to a multi-user virtual reality platform to improve interdisciplinary decision making through optimized visualization support and integrated collaboration in virtual space.

7. Conclusions

One of the top priorities in the design and construction of sustainable industrial buildings should be the minimization of the life cycle costs and environmental impacts while maximizing the flexibility and expandability of the load-bearing structure for changing production processes. When structural life cycle investigations of a typical industrial building are already considered in the early design stage and production layout planning is integrated, a balance between flexibility, sustainability, and costs can be achieved and the structure will be more easily adaptable to changing production layouts in the future. To make the quality of sustainable industrial buildings measurable, assessable and comparable, the POD model framework was developed and presented in this paper. The POD model framework provides real-time feedback on the LCC, LCA, recycling potential, and flexibility performance of structural and enclosure building systems incorporating production layout scenarios. Integrating LCC, LCA and recycling potential assessment into early structural design brings transparency to the design process and increases designers' awareness of the resource efficiency of the building. A novel rating system was implemented to efficiently compare and rank variants based on their performance, and to provide user-specific performance weighting to account for designer preferences in the design process.

The framework was tested in a variant study on a pilot project from the food and hygiene production. The results show that the POD model framework is efficient for studying different industrial building structures and selecting alternative building materials and structural and envelope systems with the lowest LCC, LCA, and recycling potential and the highest flexibility. A method is provided to identify potential savings in terms of the economic and environmental resource efficiency of industrial building structures at a very early design stage. Thus, the POD model can be used to gain a better understanding of the impact of different design decisions and different production layouts on the structural performance of industrial buildings.

The proposed design process can be beneficial for decision making in the early design stage of industrial buildings; however, it still requires human manipulation of parameters and prior parametric design skills. Future research will, therefore, focus on the simplification of processes to improve the usability of the POD tool. The proposed process will be implemented in a multi-objective evolutionary optimization algorithm to automate the design search and minimize the manual user manipulation. Finally, to further facilitate interdisciplinary decision making through collaborative visualization, a technique to connect the POD model framework to a multi-user VR platform will be created. Users will be able to explore the 3D building structures and production plans to interactively inspect and modify generated designs. The development of the multi-objective optimization algorithm, the framework enhancement with VR and the testing within a user study with experts will also contribute to further validate proposed models and data.

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Nomenclature

AP	Acidification Potential
BIM	Building Information Modeling
CO_2	Carbon dioxide
CC	Construction Cost
EE	Embodied energy
GFA	Gross Floor Area
GWP	Global Warming Potential
LCA	Life Cycle Assessment
MJ	Mega Joule
OC	Operation Cost
PENRT	Primary Energy Non-Renewable
PERT	Primary Energy Renewable
POD	Parametric Optimization and Decision Support
SO_2	Sulfur dioxide

References

1. United Nations Environment Programme (UNEP). *Climate Change: Status, Challenges, and Opportunities*; United Nations Environment Programme, Sustainable Buildings and Construction Initiative: Paris, France, 2007.
2. Lieder, M.; Rashid, A. Towards Circular Economy Implementation: A Comprehensive Review in Context of Manufacturing Industry. *J. Clean. Prod.* **2016**, *115*, 36–51. [CrossRef]
3. Heravi, G.; Fathi, M.; Faeghi, S. Evaluation of Sustainability Indicators of Industrial Buildings Focused on Petrochemical Projects. *J. Clean. Prod. 2015. 109*, 92–107. [CrossRef]
4. San-José Lombera, J.-T.; Garrucho Aprea, I. A system approach to the environmental analysis of industrial buildings. *Build. Environ.* **2010**, *45*, 673–683. [CrossRef]
5. Rodrigues, V.; Martins, A.A.; Nunes, M.I.; Quintas, A.; Mata, T.M.; Caetano, N. LCA of constructing an industrial building: Focus on embodied carbon and energy. *Energy Procedia* **2018**, *153*, 420–425. [CrossRef]
6. Rauf, A.; Crawford, R.H. Building service life and its effect on the life cycle embodied energy of buildings. *Energy* **2015**, *79*, 140–148. [CrossRef]
7. Gourlis, G.; Kovacic, I. Building Information Modelling for analysis of energy efficient industrial buildings—A case study. *Renew. Sustain. Energy Rev.* **2017**, *68*, 953–963. [CrossRef]
8. Reisinger, J.; Hollinsky, P.; Kovacic, I. Design Guideline for Flexible Industrial Buildings Integrating Industry 4.0 Parameters. *Sustainability* **2021**, *13*, 10627. [CrossRef]
9. Peukert, B.; Benecke, S.; Clavell, J.; Neugebauer, S.; Nissen, N.F.; Uhlmann, E.; Lang, K.-D.; Finkbeiner, M. Addressing Sustainability and Flexibility in Manufacturing Via Smart Modular Machine Tool Frames to Support Sustainable Value Creation. *Procedia CIRP* **2015**, *29*, 514–519. [CrossRef]
10. Gosling, J.; Naim, M.; Sassi, P.; Iosif, L.; Lark, R. Flexible Buildings for an Adaptable and Sustainable Future. In Proceedings of the 24th Annual ARCOM Conference, Cardiff, UK, 1–3 September 2008.
11. Cardin, M.-A.; Ranjbar-Bourani, M.; de Neufville, R. Improving the Lifecycle Performance of Engineering Projects with Flexible Strategies: Example of On-Shore LNG Production Design. *Syst. Eng.* **2015**, *18*, 253–268. [CrossRef]
12. Madson, K.M.; Franz, B.; Molenaar, K.R.; Kremer, G.O. Strategic development of flexible manufacturing facilities. *Eng. Constr. Archit. Manag.* **2020**, *27*, 1299–1314. [CrossRef]
13. Sahinidis, N.V.; Grossmann, I.E. Multiperiod investment model for processing networks with dedicated and flexible plants. *Ind. Eng. Chem. Res.* **1991**, *30*, 1165–1171. [CrossRef]
14. Chen, D.; Heyer, S.; Seliger, G.; Kjellberg, T. Integrating sustainability within the factory planning process. *CIRP Annals* **2012**, *61*, 463–466. [CrossRef]
15. Burggräf, P.; Dannapfel, M.; Schneidermann, D.; Esfahani, M.E.; Schwamborn, N. Integrated factory modelling: Using BIM to disrupt the interface between manufacturing and construction in factory planning. *WIT Trans. Built Environ.* **2019**, *192*, 143–155. [CrossRef]

16. Wiendahl, H.-P.; ElMaraghy, H.; Nyhuis, P.; Zäh, M.; Duffie, N.; Brieke, M. Changeable Manufacturing—Classification, Design and Operation. *CIRP Ann.* **2007**, *56*, 783–809. [CrossRef]
17. Bejjani, C.; Utsch, J.; Thiele, T.; Meisen, T.; Jeschke, S.; Burggräf, P. Flow Chart Based Information Modeling for Factory Planning. *Procedia CIRP* **2018**, *72*, 410–415. [CrossRef]
18. Graefenstein, J.; Winkels, J.; Lenz, L.; Weist, K.; Krebil, K.; Gralla, M. A Hybrid Approach of Modular Planning—Synchronizing Factory and Building Planning by Using Component based Synthesis. In Proceedings of the 53rd Annual Hawaii International Conference on System Sciences, Maui, HI, USA, 7–10 January 2020. [CrossRef]
19. Opher, T.; Duhamel, M.; Posen, I.D.; Panesar, D.K.; Brugmann, R.; Roy, A.; Zizzo, R.; Sequeira, L.; Anvari, A.; MacLean, H.L. Life cycle GHG assessment of a building restoration: Case study of a heritage industrial building in Toronto, Canada. *J. Clean. Prod.* **2021**, *279*, 123819. [CrossRef]
20. Bonamente, E.; Cotana, F. Carbon and Energy Footprints of Prefabricated Industrial Buildings: A Systematic Life Cycle Assessment Analysis. *Energies* **2015**, *8*, 12685–12701. [CrossRef]
21. Tulevech, S.M.; Hage, D.J.; Jorgensen, S.K.; Guensler, C.L.; Himmler, R.; Gheewala, S.H. Life cycle assessment: A multi-scenario case study of a low-energy industrial building in Thailand. *Energy Build.* **2018**, *168*, 191–200. [CrossRef]
22. Li, S.; Lu, Y.; Kua, H.W.; Chang, R. The economics of green buildings: A life cycle cost analysis of non-residential buildings in tropic climates. *J. Clean. Prod.* **2020**, *252*, 119771. [CrossRef]
23. Brinks, P.; Kornadt, O.; Oly, R. Development of concepts for cost-optimal nearly zero-energy buildings for the industrial steel building sector. *Appl. Energy* **2016**, *173*, 343–354. [CrossRef]
24. Weerasinghe, A.S.; Ramachandra, T.; Rotimi, J.O.B. Comparative life-cycle cost (LCC) study of green and traditional industrial buildings in Sri Lanka. *Energy Build.* **2021**, *234*, 110732. [CrossRef]
25. Kovacic, I.; Waltenbereger, L.; Gourlis, G. Tool for life cycle analysis of facade-systems for industrial buildings. *J. Clean. Prod.* **2016**, *130*, 260–272. [CrossRef]
26. Lee, B.; Pourmousavian, N.; Hensen, J.L.M. Full-factorial design space exploration approach for multi-criteria decision making of the design of industrial halls. *Energy Build.* **2016**, *117*, 352–361. [CrossRef]
27. Glumac, B.; Islam, N. Housing preferences for adaptive re-use of office and industrial buildings: Demand side. *Sustain. Cities Soc.* **2020**, *62*, 102379. [CrossRef]
28. Moline, A. Recipe for Change: The Flexible Food Processing Plant of the Future. In *DesignFlex2030*; Industrial Asset Management Council (IAMC): Peachtree Corners, GA, USA, 2015.
29. Moline, A. Rx for change: The flexible biopharma facility of the future. In *DesignFlex2030*; Industrial Asset Management Council (IAMC): Peachtree Corners, GA, USA, 2017.
30. Marjaba, G.; Chidiac, S.E. Sustainability and resiliency metrics for buildings—Critical review. *Build. Environ.* **2016**, *101*, 116–125. [CrossRef]
31. Kamalakkannan, S.; Kulatunga, A.K. Optimization of eco-design decisions using a parametric life cycle assessment. *Sustain. Prod. Consum.* **2021**, *27*, 1297–1316. [CrossRef]
32. Haymaker, J.; Bernal, M.; Marshal, M.T.; Okhoya, V.; Szilasi, A.; Razaee, R.; Chen, C.; Salveson, A.; Brechtel, J.; Deckinga, L.; et al. Design space construction: A framework to support collaborative, parametric decision making. *J. Inf. Technol. Constr.* **2018**, *23*, 157–178. Available online: http://www.itcon.org/2018/8 (accessed on 20 December 2021).
33. Basic, S.; Hollberg, A.; Galimshina, A.; Habert, G. A design integrated parametric tool for real-time Life Cycle Assessment—Bombyx project. In Proceedings of the Sustainable Built Environment D-A-CH Conference, Graz, Austria, 11—14 September 2019. IOP Conference Series: Earth and Environmental Science. [CrossRef]
34. Fufa, S.M.; Skaar, C.; Gradeci, K.; Labonnote, N. Assessment of greenhouse gas emissions of ventilated timber wall constructions based on parametric LCA. *J. Clean. Prod.* **2018**, *197*, 34–46. [CrossRef]
35. Reisinger, J.; Kovacic, I.; Kaufmann, H.; Kan, P.; Podkosova, I. Framework Proposal for a BIM-Based Digital Platform for Flexible Design and Optimization of Industrial Buildings for Industry 4.0. In Proceedings of the 37th International Conference of CIB W78, Sao Paulo, Brazil, 18–20 August 2020; pp. 401–415. [CrossRef]
36. Reisinger, J.; Knoll, M.; Kovacic, I. Design space exploration for flexibility assessment and decision making support in integrated industrial building design. *Optim. Eng.* **2021**, *22*, 1693–1725. [CrossRef]
37. Reisinger, J.; Zahlbruckner, M.A.; Kovacic, I.; Kán, P.; Wang-Sukalia, X.; Kaufmann, H. Integrated multi-objective evolutionary optimization of production layout scenarios for parametric structural design of flexible industrial buildings. *J. Build. Eng.* **2022**, *46*, 103766. [CrossRef]

8. Marrero, M.; Rivero-Camacho, C.; Martínez-Rocamora, A.; Alba-Rodríguez, M.D.; Solís-Guzmán, J. Life Cycle Assessment of Industrial Building Construction and Recovery Potential. Case Studies in Seville. *Processes* **2022**, *10*, 76. [CrossRef]

9. Oti, A.H.; Tizani, W. BIM extension for the sustainability appraisal of conceptual steel design. *Adv. Eng. Inform.* **2015**, *29*, 28–46. [CrossRef]

0. Sanchez, B.; Esfahani, M.E.; Haas, C. A methodology to analyze the net environmental impacts and building's cost performance of an adaptive reuse project: A case study of the Waterloo County Courthouse renovations. *Environ. Syst. Decis.* **2019**, 39. [CrossRef]

1. Raposo, C.; Rodrigues, F.; Rodrigues, H. BIM-based LCA assessment of seismic strengthening solutions for reinforced concrete precast industrial buildings. *Innov. Infrastruct. Solut.* **2019**, *4*, 1–10. [CrossRef]

42. Vilutiene, T.; Kumetaitis, G.; Kiaulakis, A.; Kalibatas, D. Assessing the Sustainability of Alternative Structural Solutions of a Building: A Case Study. *Buildings* **2020**, *10*, 36. [CrossRef]
43. Hens, I.; Solnosky, R.; Brown, N.C. Design space exploration for comparing embodied carbon in tall timber structural systems. *Energy Build.* **2021**, *244*, 110983. [CrossRef]
44. Brown, N.C.; Jusiega, V.; Mueller, C.T. Implementing data-driven parametric building design with a flexible toolbox. *Autom. Constr.* **2020**, *118*, 103252. [CrossRef]
45. Apellániz, D.; Pasanen, P.; Gengnagel, C. A Holistic and Parametric Approach for Life Cycle Assessment in the Early Design Stages. In Proceedings of the 12th annual Symposium on Simulation for Architecture and Urban Design (SimAUD), Online, 7 October 2020–1 May 2021.
46. McNeel, A. Grasshopper. 2021. Available online: https://www.rhino3d.com/6/new/grasshopper (accessed on 20 December 2021).
47. Preisinger, C. Karamba3D. 2021. Available online: https://www.karamba3d.com/ (accessed on 20 December 2021).
48. BKI-Baukosteninformationszentrum, BKI Baukosten Gebäude. *Positionen und Bauelemente Neubau 2020-Teil 1-3: Statistische Kostenkennwerte*; Müller Rudolf: Stuttgart, Germany, 2020; Volume 1, 2515p.
49. BaubookGmbH. Baubook-Die Datenbank für ökologisches Bauen & Sanieren. Available online: http://www.baubook.info/ (accessed on 10 December 2021).
50. ISO/TC59, B.C. *ISO 15686-5-Buildings and Constructed Assets—Service Life Planning-Part 5: Life-Cycle Costing*; ISO International Organization for Standardization: Geneva, Switzerland, 2017; p. 43.
51. Österreichisches Institut für Baubiologie und -ökologie GmbH(IBO). *OI3-Berechnungsleitfaden Version 4.0*; IBO—Österreichisches Institut für Bauen und Ökologie GmbH: Vienna, Austria, 2018; p. 21.
52. Österreichisches Institut für Baubiologie und -ökologie GmbH(IBO). *Leitfaden zur Berechnung des Entsorgungsindikators EI Kon von Bauteilen*; IBO—Österreichisches Institut für Bauen und Ökologie GmbH: Vienna, Austria, 2020; 15p.
53. McNeel, A. Rhinoceros 3D. 2020. Available online: https://www.rhino3d.com/ (accessed on 20 December 2020).
54. Deutsche Gesellschaft für Nachhaltiges Bauen (DGNB). *DGNB System—Kriterienkatalog Gebäude Neubau*; DGNB: Stuttgart, Germany, 2018; p. 57.
55. Ylmén, P.; Mjörnell, K.; Berlin, J.; Arfvidsson, J. Approach to manage parameter and choice uncertainty in life cycle optimisation of building design: Case study of optimal insulation thickness. *Build. Environ.* **2021**, *191*, 107544. [CrossRef]