buildings

MDPI

Article

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

Julia Reisinger *, Stefan Kugler, Iva Kovacic and Maximilian Knoll

Institute for Interdisciplinary Construction Process Management, Department of Integrated Planning and Industrial Building, TU Wien, 1040 Vienna, Austria; e1228839@student.tuwien.ac.at (S.K.); iva.kovacic@tuwien.ac.at (I.K.); maximilian.knoll@tuwien.ac.at (M.K.)
* Correspondence: julia.reisinger@tuwien.ac.at

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

Citation: Reisinger, J.; Kugler, S.; Kovacic, I.; Knoll, M. 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**, *12*, 162. https://doi.org/10.3390/buildings12020162

Academic Editor: Manuel Parente

Received: 22 December 2021
Accepted: 1 February 2022
Published: 2 February 2022

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 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$_2$eq/m^3/year for a 20-year lifetime and 3516 kgCO$_2$eq/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$_2$eq/m^3 and 33.95 kgCO$_2$eq/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.

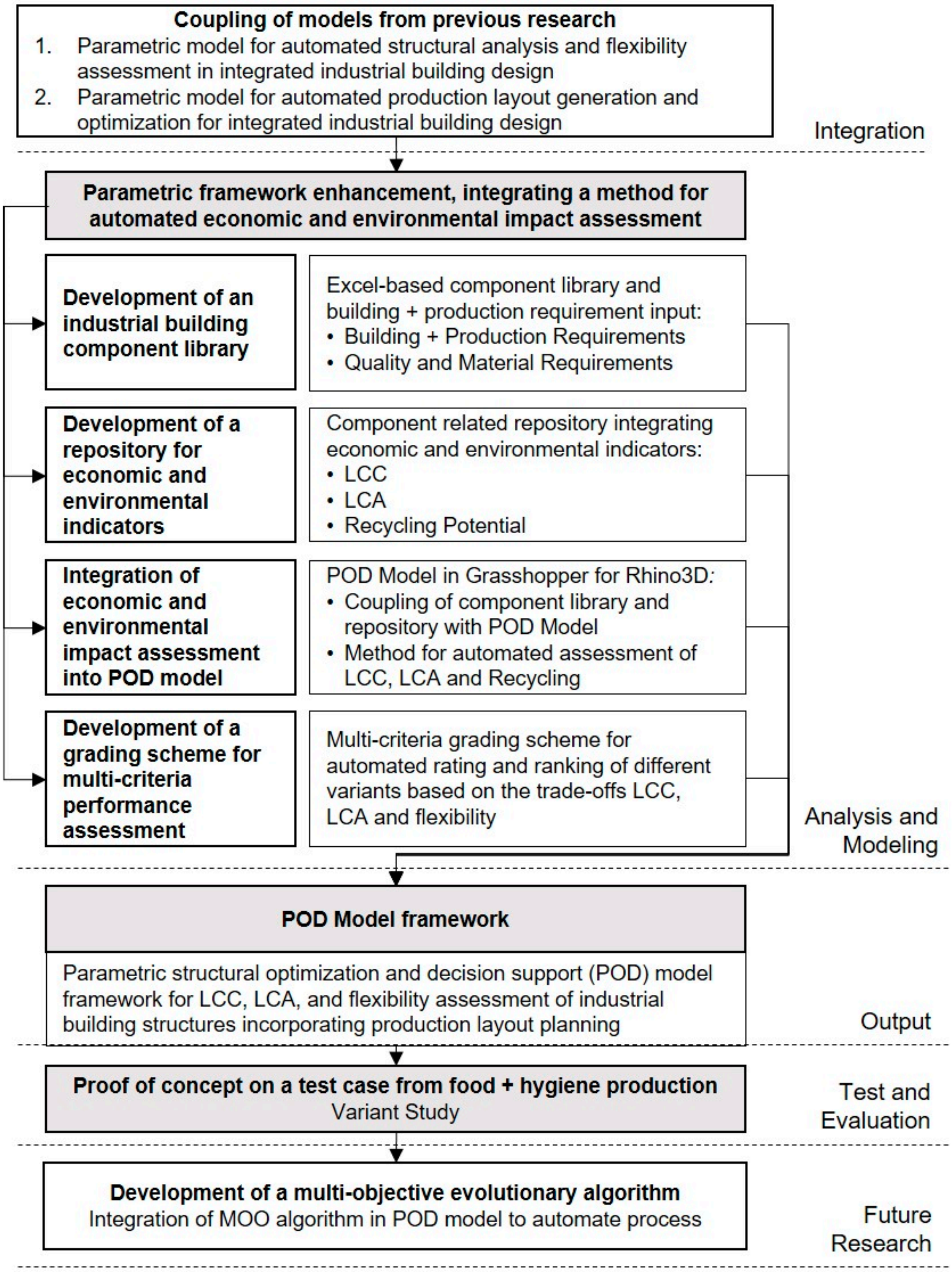

Figure 1. Overview of the research design and the scope of the paper.

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.

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.

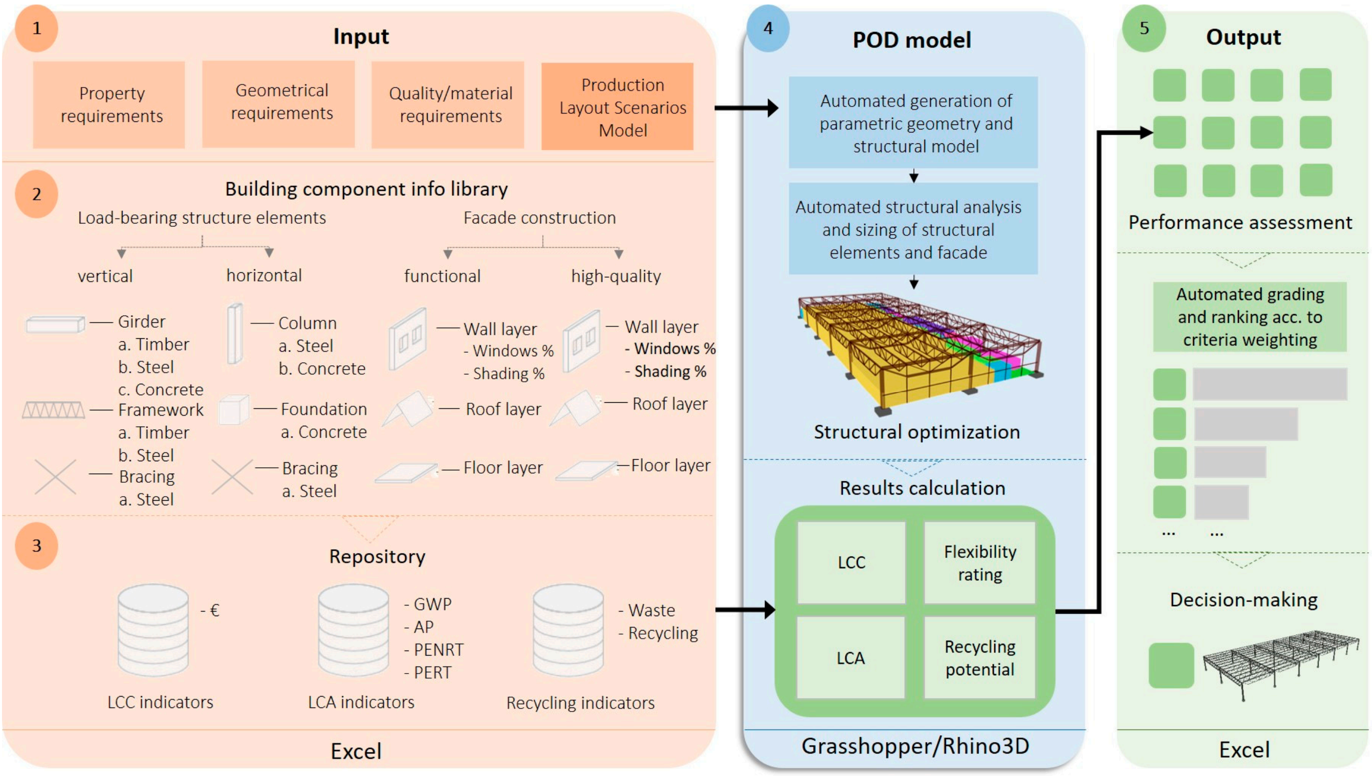

Figure 2. The POD model framework.

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.

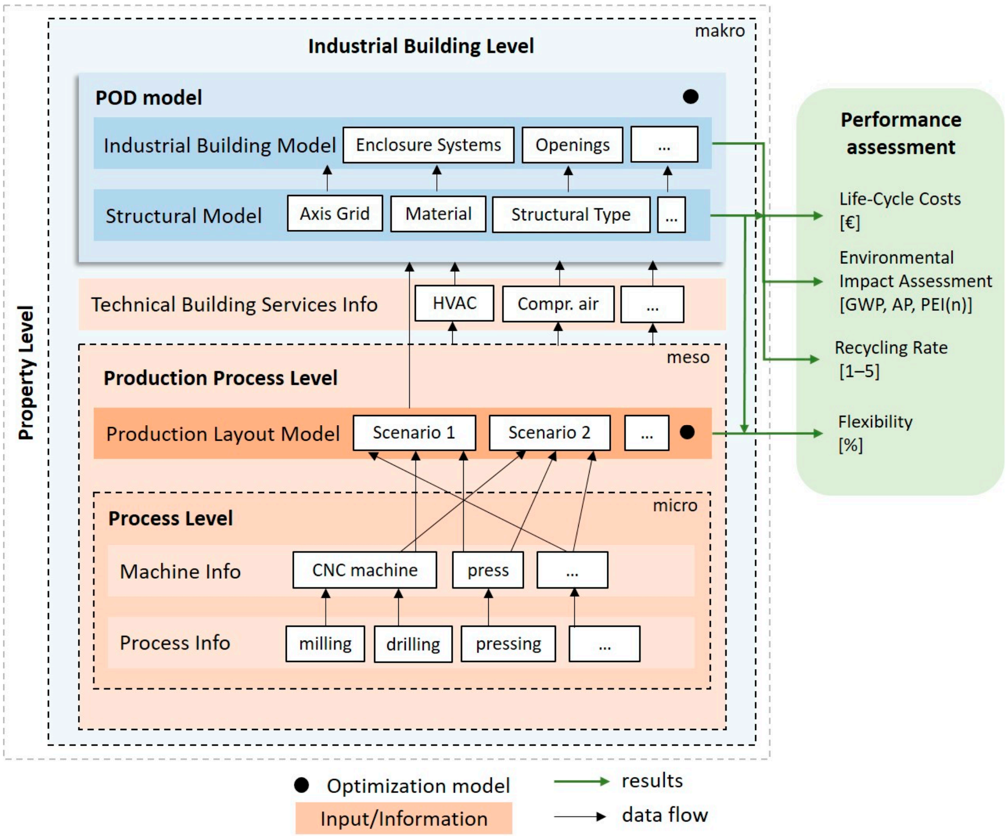

Figure 3. Framework for integrated industrial building design to enable flexible structural and production layout planning.

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.

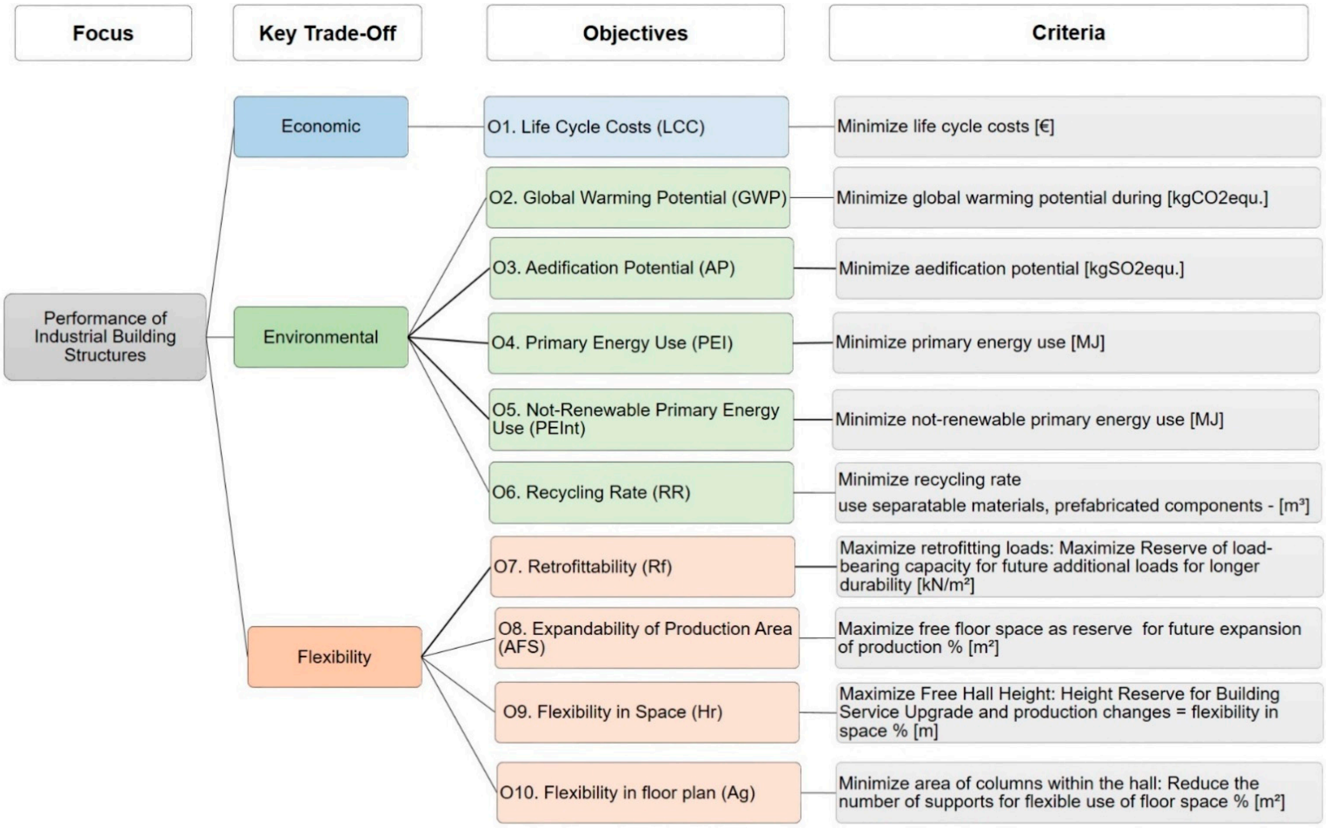

Figure 4. Key trade-offs and related objectives included in the POD model framework for performance assessment of industrial building structures.

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]:

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

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.

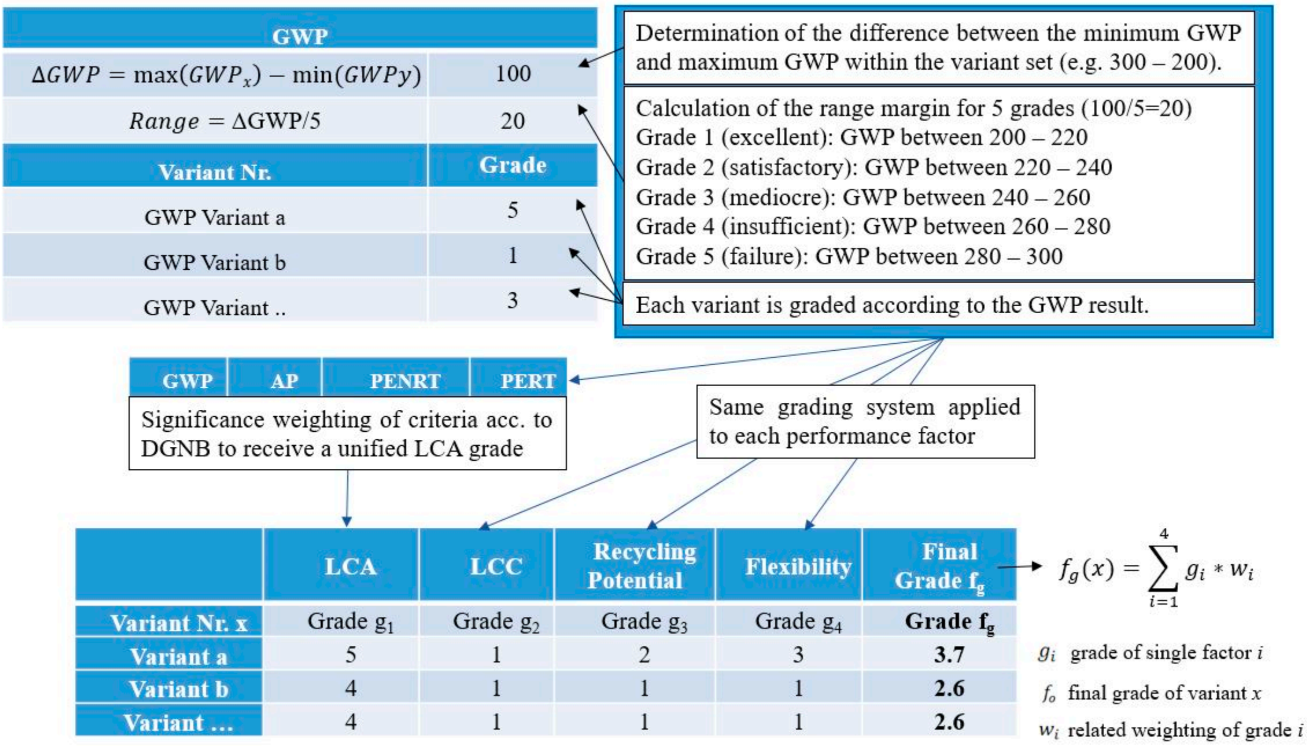

Figure 5. Grading methodology to make the performance of building variants rapidly comparable.

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 115200 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.

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].

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

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$_2$equ.	AP t SO$_2$equ.	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$_2$equ.	AP t SO$_2$equ.	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$_2$equ.**	**AP t SO$_2$equ.**	**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 x 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 tCO$_2$equ/m^2 and after 50 years 1480.40 tCO$_2$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 tCO$_2$equ/m^2) but a slightly higher GWP result after 50 years (1584.75 tCO$_2$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).

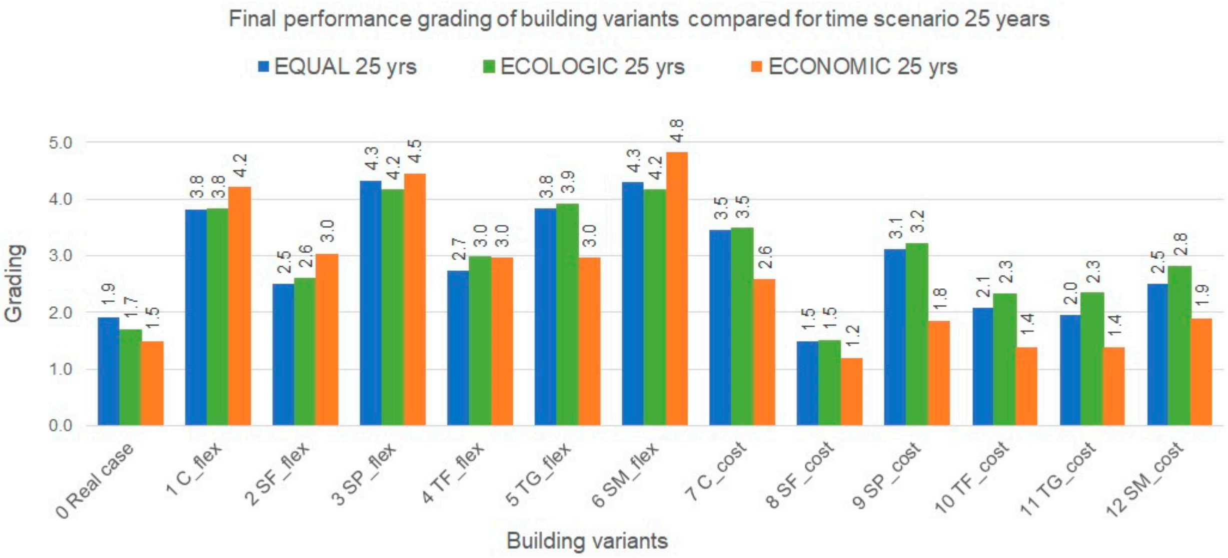

Figure 6. Final performance grading and comparison of the examined building variants for the time scenario 25 years and the weighting scenarios (equal, ecologic and economic).

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.

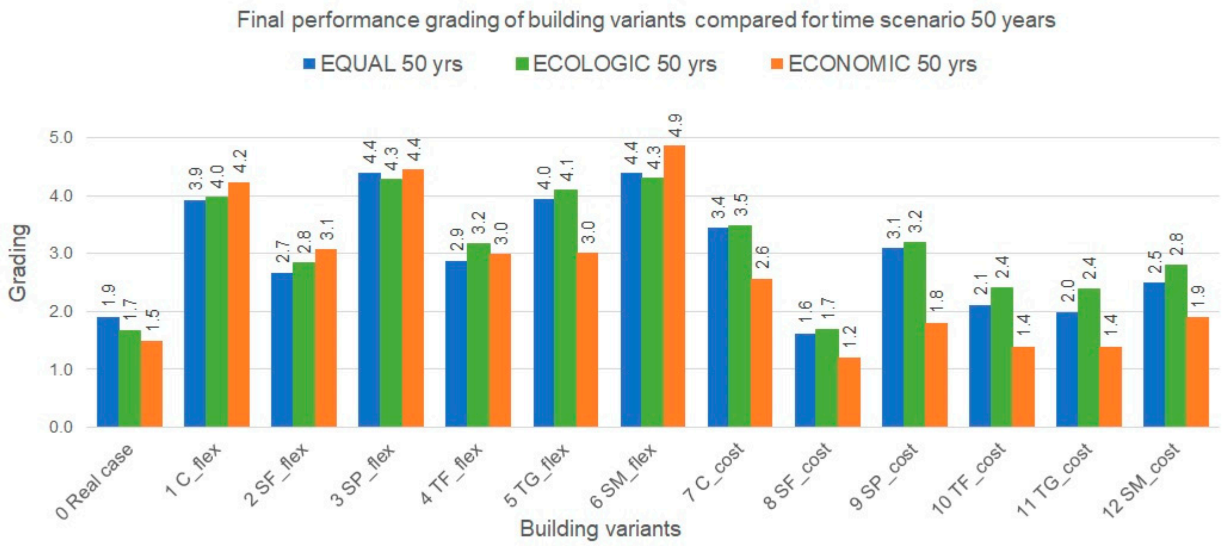

Figure 7. Final performance grading and comparison of the examined building variants for the time scenario 50 years and the weighting scenarios (equal, ecologic and economic).

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.

Author Contributions: Conceptualization, J.R.; methodology, J.R.; software, S.K. and M.K.; validation, J.R., S.K.; formal analysis, J.R.; investigation, J.R. and S.K.; resources, J.R., S.K. and M.K.; data curation, J.R.; writing—original draft preparation, J.R.; writing—review and editing, J.R. and I.K.; visualization, J.R.; supervision, I.K.; project administration, J.R.; funding acquisition, I.K. and J.R. All authors have read and agreed to the published version of the manuscript.

Funding: The authors would like to acknowledge the support by the Austrian funding institution FFG (Österreichische Forschungsförderungsgesellschaft) for the research project "BIMFlexi" within the FFG BRIDGE programme (Grant No. 877159). Open Access Funding by TU Wien Bibliothek.

Institutional Review Board Statement: Not applicable as the study did not involve animals or humans.

Informed Consent Statement: Not applicable as the study did not involve humans.

Data Availability Statement: The data presented in this study are available on request from the corresponding author.

Acknowledgments: The authors would particularly like to thank the industry partners who provided use cases and the Austrian funding agency FFG for the research funding. The authors acknowledge TU Wien Bibliothek for financial support through its Open Access Funding Programme.

Conflicts of Interest: The authors declare no conflict of interest. The funders had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript, or in the decision to publish the results.

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. https://doi.org/10.1016/j.jclepro.2015.12.042.
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. https://doi.org/10.1016/j.jclepro.2015.06.133.
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. https://doi.org/10.1016/j.buildenv.2009.08.012.
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. https://doi.org/10.1016/j.egypro.2018.10.018.
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. https://doi.org/10.1016/j.energy.2014.10.093.
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. https://doi.org/10.1016/j.rser.2016.02.009.
8. Reisinger, J.; Hollinsky, P.; Kovacic, I. Design Guideline for Flexible Industrial Buildings Integrating Industry 4.0 Parameters. *Sustainability* **2021**, *13*, 10627. https://doi.org/10.3390/su131910627.
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. https://doi.org/10.1016/j.procir.2015.02.181.
10. Gosling, J.; Naim, M.; Sassi, P.; Iosif, L.; Lark, R. Flexible Buildings for an Adaptable and Sustainable Future; In Proceedings of 24th Annual ARCOM Conference, 1–3 September 2008, Cardiff, UK
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. https://doi.org/10.1002/sys.21301.
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. https://doi.org/10.1108/ECAM-03-2019-0139.
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. https://doi.org/10.1021/ie00054a015.
14. Chen, D.; Heyer, S.; Seliger, G.; Kjellberg, T. Integrating sustainability within the factory planning process. *CIRP Annals* **2012**, *61*, 463–466. https://doi.org/10.1016/j.cirp.2012.03.067.

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. 10.2495/BIM190131.
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. https://doi.org/10.1016/j.cirp.2007.10.003.
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. https://doi.org/10.1016/j.procir.2018.03.259.
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 the Proceedings of the 53rd Annual Hawaii International Conference on System Sciences, Maui, HI, USA, 7–10 January 2020. https://doi.org/10.24251/HICSS.2020.806.
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. https://doi.org/10.1016/j.jclepro.2020.123819.
20. Bonamente, E.; Cotana, F. Carbon and Energy Footprints of Prefabricated Industrial Buildings: A Systematic Life Cycle Assessment Analysis. *Energies* **2015**, *8*, 12685–12701.
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. https://doi.org/10.1016/j.enbuild.2018.03.011.
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. https://doi.org/10.1016/j.jclepro.2019.119771.
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. https://doi.org/10.1016/j.apenergy.2016.04.007.
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. https://doi.org/10.1016/j.enbuild.2021.110732.
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.
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. https://doi.org/10.1016/j.enbuild.2015.09.028.
27. Glumac, B.; Islam, N. Housing preferences for adaptive re-use of office and industrial buildings: Demand side. *Sustain. Cities Soc.* **2020**, *62*, 102379. https://doi.org/10.1016/j.scs.2020.102379.
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. 10.1016/j.buildenv.2016.03.002.
31. Kamalakkannan, S.; Kulatunga, A.K. Optimization of eco-design decisions using a parametric life cycle assessment. *Sustain. Prod. Consum.* **2021**, *27*, 1297–1316. https://doi.org/10.1016/j.spc.2021.03.006.
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 month year).
33. Basic, S.; Hollberg, A.; Galimshina, A.; Habert, G. A design integrated parametric tool for real-time Life Cycle Assessment—Bombyx project. In the Proceedings of the Sustainable Built Environment D-A-CH Conference, Graz, Austria, 11—14 September 2019; IOP Conference Series: Earth and Environmental Science;. https://doi.org/10.1088/1755-1315/323/1/012112.
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. https://doi.org/10.1016/j.jclepro.2018.06.006.
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 ICCCBE/W78 In the Proceedings of the 37th International Conference of CIB W78, Sao Paulo, Brazil, 18–20 August, pp. 401–415. https://doi.org/10.46421/2706-6568.37.2020.paper029.
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. https://doi.org/10.1007/s11081-021-09614-2.
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. https://doi.org/10.1016/j.jobe.2021.103766.
38. 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.
39. Oti, A.H.; Tizani, W. BIM extension for the sustainability appraisal of conceptual steel design. *Adv. Eng. Inform.* **2015**, *29*, 28–46. https://doi.org/10.1016/j.aei.2014.09.001.
40. 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*. https://doi.org/10.1007/s10669-019-09734-2.

41. 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, doi:51. 10.1007/s41062-019-0239-7.
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.
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. https://doi.org/10.1016/j.enbuild.2021.110983.
44. Brown, N.C.; Jusiega, V.; Mueller, C.T. Implementing data-driven parametric building design with a flexible toolbox. *Autom. Constr.* **2020**, *118*, 103252. https://doi.org/10.1016/j.autcon.2020.103252.
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. Vol. 1. 2020, Stuttgart: Müller Rudolf. 2515.
49. BaubookGmbH. Baubook-Die Datenbank für ökologisches Bauen & Sanieren; Available from: 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: Geneve, 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. 15 pages
53. McNeel, A. Rhinoceros 3D. 2020; Available from: 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. https://doi.org/10.1016/j.buildenv.2020.107544.