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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 modelling. 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

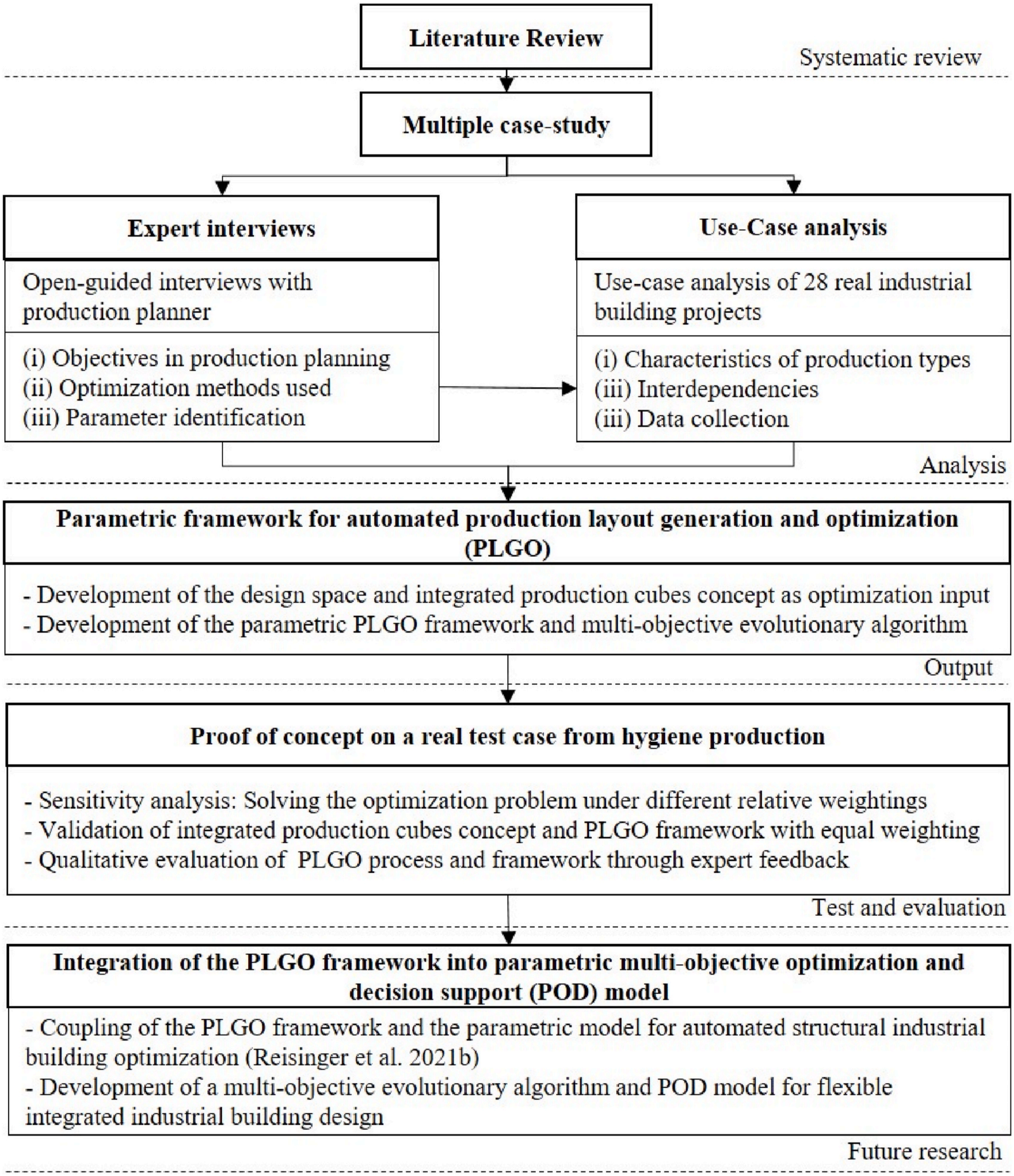



**Fig. 1.** Overview of the research design and the scope of the paper.

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-

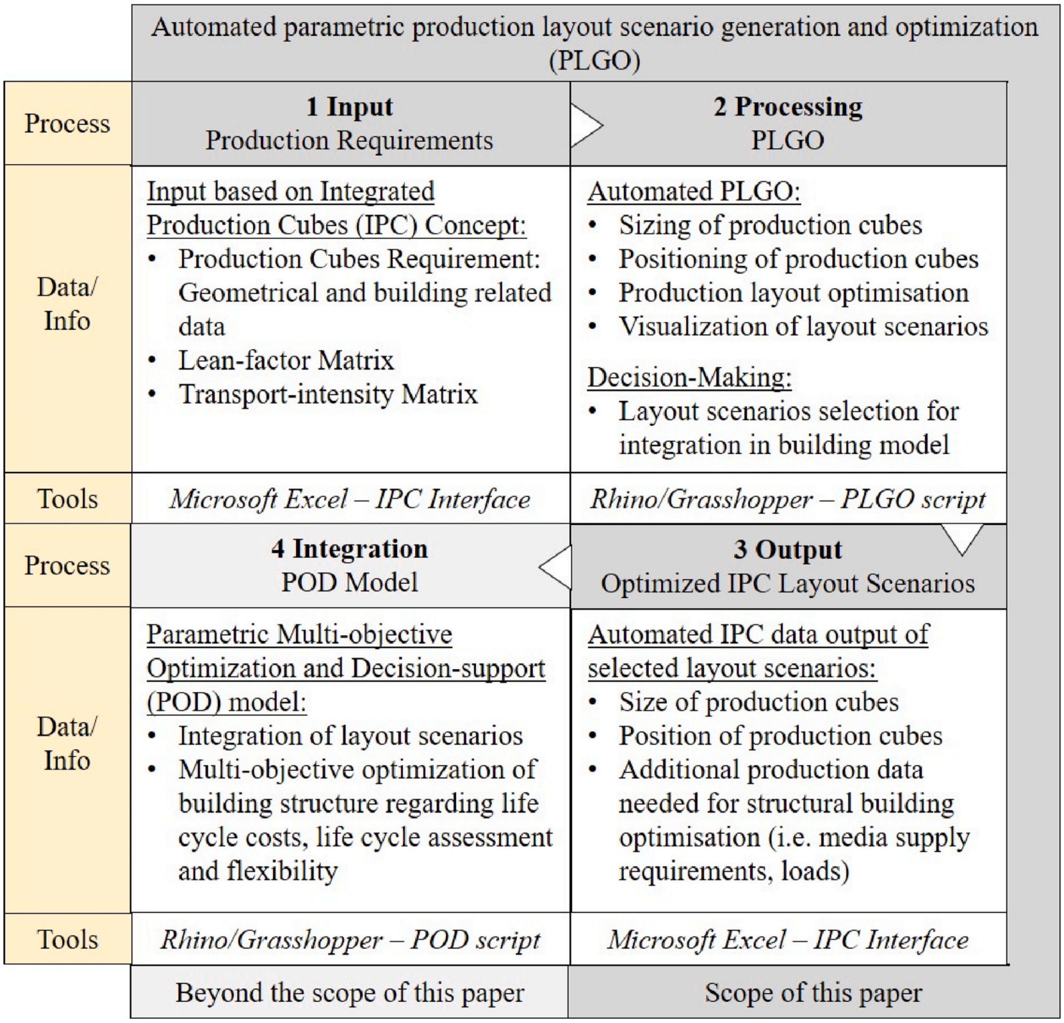



**Fig. 2.** Design process, data and tools of the parametric PLGO framework and scope of the paper.

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-

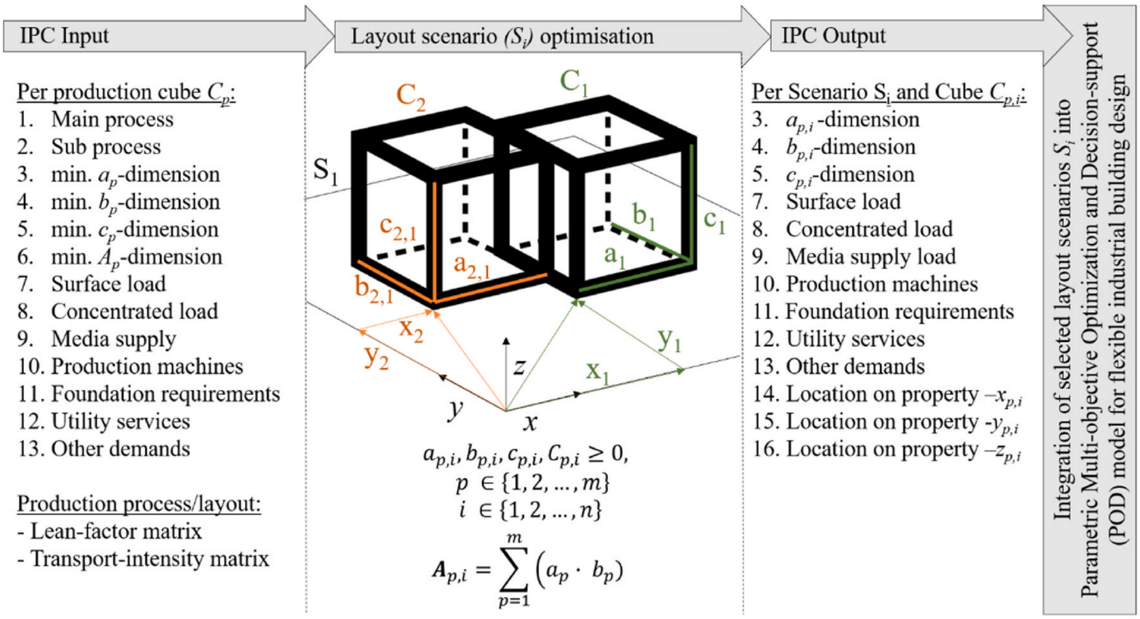



**Fig. 3.** Integrated production cubes concept: Geometrical formulation and respected data.

(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.

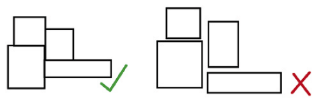
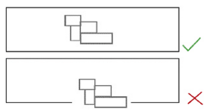
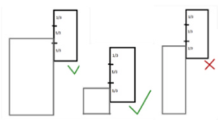
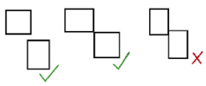
| C | Constraints | Formulation | Description |
|---|---|---|---|
| $c_1$ | *Cohesive layout:* The individual production cube areas ($A_q$, $A_r$) must not overlap with each other. | $A_q \cap A_r = \varnothing$ with $q \neq r$ and q, r = {1,2, …,m} At least one edge of each cube must overlap with another 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* | $g_5 = \frac{\left( \sum_{p=1}^{m} \sum_{q=p}^{m} \left( abs(x_p - x_q) + abs(y_p - y_q) \right) * T_{p,q} \right)}{\left( \sum_{p=1}^{m} \sum_{q=p}^{m} T_{p,q} \right) * (a_s + b_s)}$ $a_s$, $b_s$… 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.

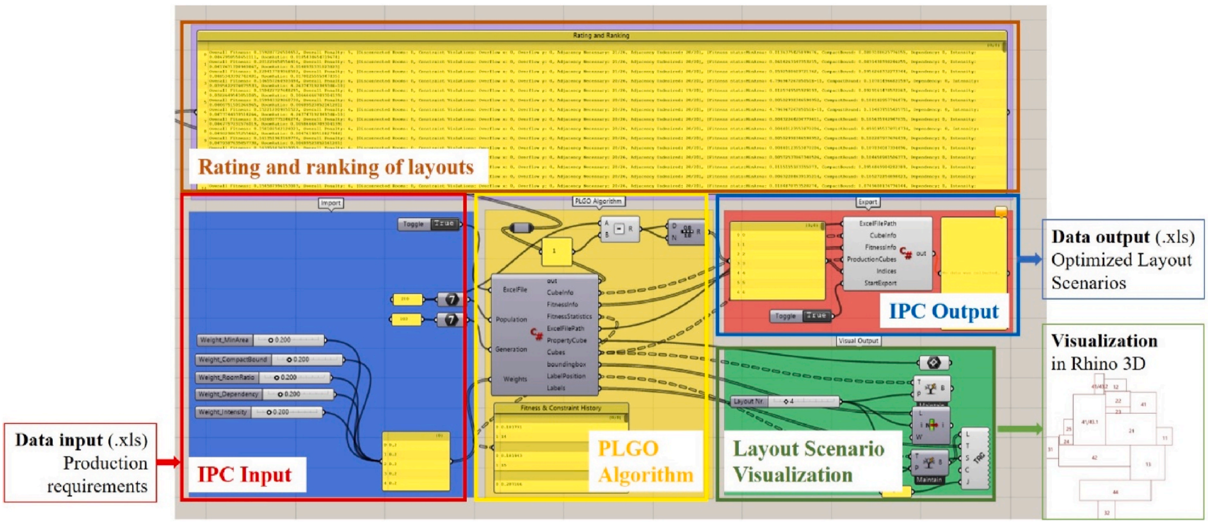



**Fig. 5.** The parametric PLGO framework in Grasshopper for Rhino 3D, describing the data flow of input and output and the layout visualization in Rhino 3D.

| | Minimum cube dimensions | | |
|---|---|---|---|
| Cube ID | 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 |

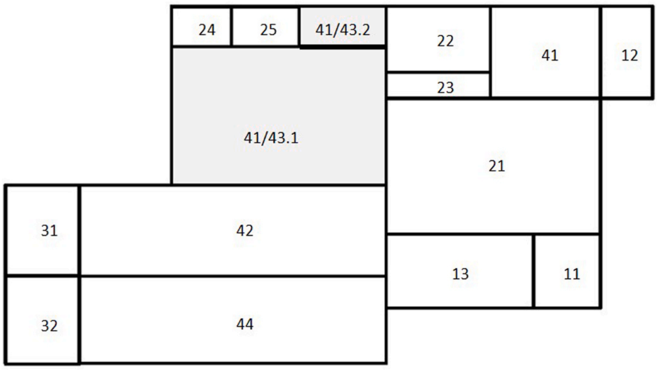



**Fig. 6.** Real production layout of the test case from the hygiene production and production cubes requirements of minimum dimensions of each production cube with its main and sub process.

**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.

$$f_o(x) = g_i * 1.0 \cdot with \cdot i = 1, \ldots, 5 \tag{2}$$

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 $i=1,\ldots,5$ | | | | |
|---|---|---|---|---|---|---|
| | | 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

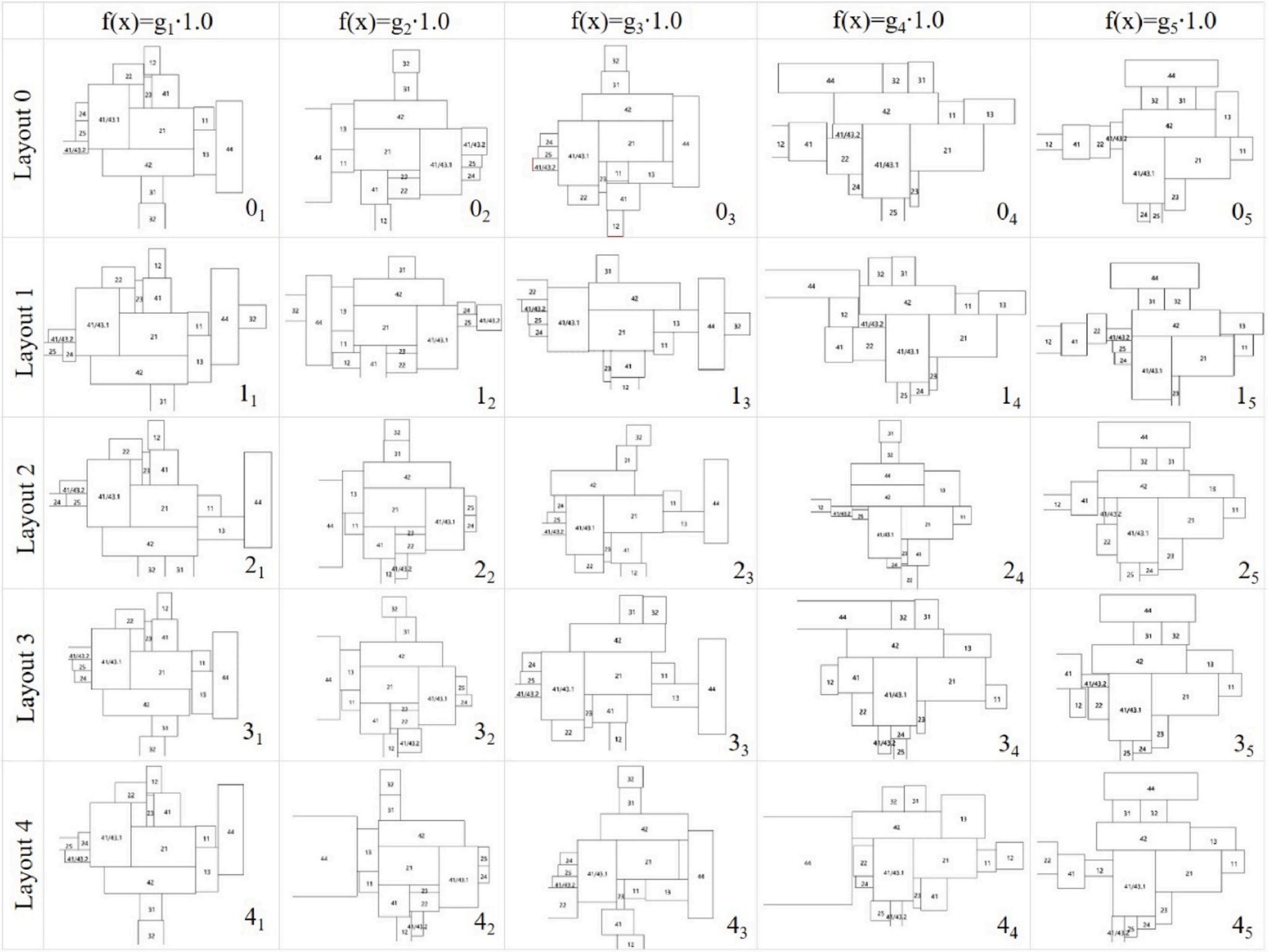



**Fig. 7.** Visualization and comparison of the generated best-rated layouts received from the sensitivity analysis per weighting scenario.

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%.

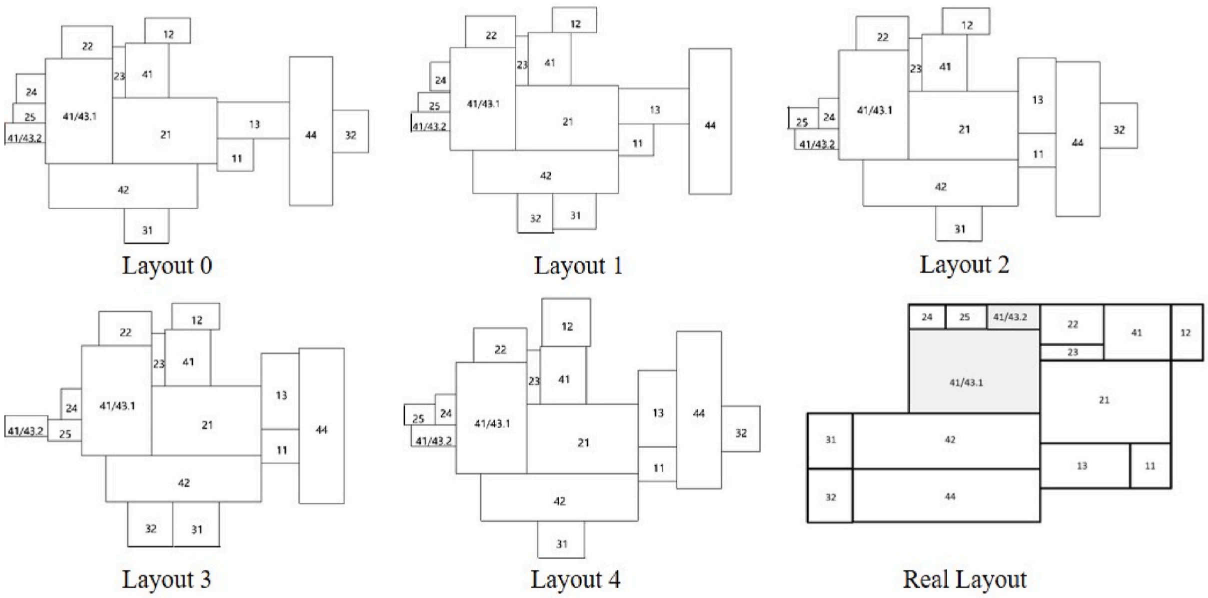



**Fig. 8.** Best-rated layout scenarios generated and the real layout of the test case.

**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 |
| | | ∑ | 12 723.7$m^2$ | | ∑ (**Δ**) | 12 807.9$m^2$ | −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

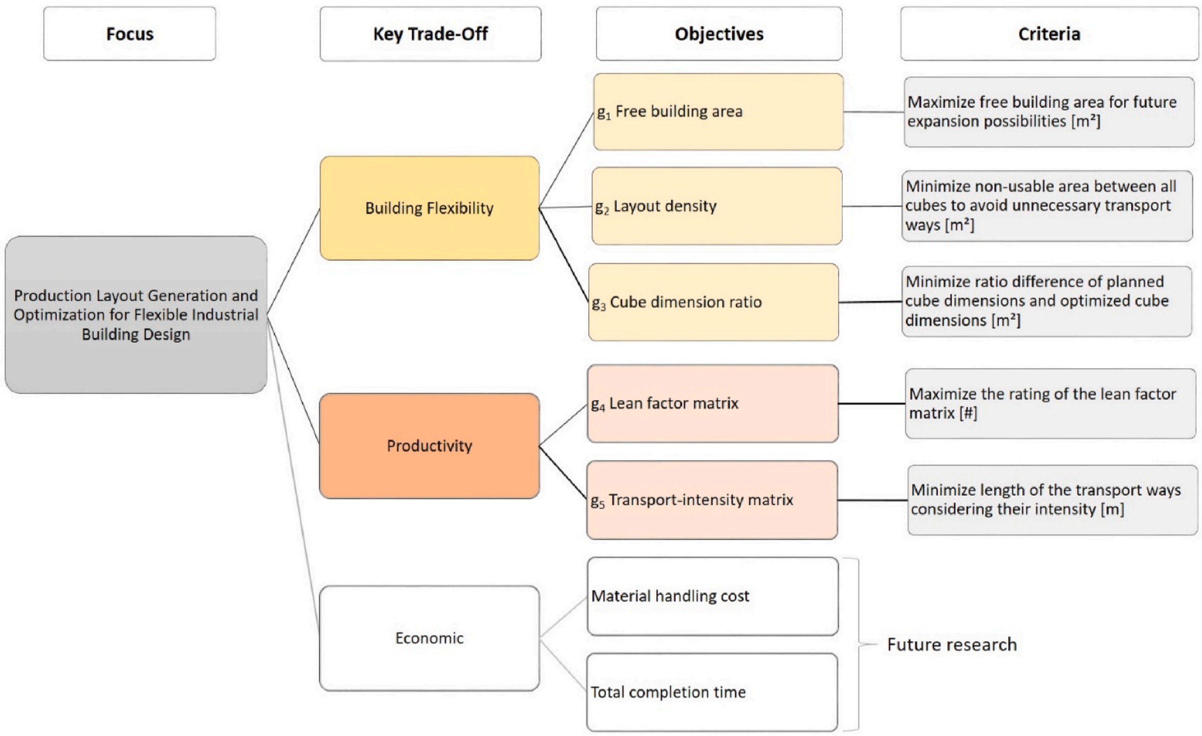



**Fig. 9.** Key trade-offs and objectives respected in the PLGO framework (yellow and orange boxes) and objectives which can be integrated in future research (white boxes). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

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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## 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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