



Integration of Algorithm-Based Optimization into the Design Process of Industrial Buildings: A Case Study

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Abstract. Algorithm-based optimization is widely applied in many fields like industrial production, resulting in state-of-the-art workflows in the production process optimization. This project takes the cultural lag of conventional industrial architecture design as a motivation to investigate the implementation of algorithm-based optimization into traditional design processes. We argue that an enhanced way of architectural decision-making is possible. Current approaches use a translation of the whole design problem into a single, overly complicated optimization system. Contrary to that, this paper presents a novel workflow that defines precise design steps and applies optimizations only if suitable. Furthermore, this method can generate relevant results for factory planning design problems with contradicting factors, making it a promising approach for the complex challenges of i.e. resource-efficient building.

Keywords: Algorithm-based optimization · Evolutionary Multi-objective Optimization · Industrial architecture · Architectural design · Design methodology

1 Introduction on Form Finding

Designing from the abstract to the concrete implies a series of different transformation, evaluation, and decision-making processes [2]. In traditional design processes the background or intuition of the designer serves as a basis for the decision-making of the iterative actions that give form to the object of design. Although the design process is generally non-linear, it renders strict, systematic methods that hamper an integral part of the process: experimentation [3]. Nowadays, facing the information age, decision-making and all its facets are increasingly challenging to obtain. In the past, interdisciplinary approaches to design strategies have proven to be successful. The interactions between computer science, mathematics, and architecture have led to the invention of CAD software, for example, from which *Building Information Modeling* (BIM) or parametric applications have evolved. However, the spread of new technologies, such as form-finding tools, is very slow, and their utilization in the architectural design process

is scarce [14]. New digital methods are no longer merely a digitalization of the conventional analog planning process. They could also be implemented into design processes to enhance the decision-making workflow when working with complex programs as industrial facilities.

1.1 Form Finding in Industrial Architecture

Industrial production is known for its advance in process optimization, economic efficiency, and hierarchical structures. Hence, factory planning requires a different design approach than conventional projects. A specific, clearly defined program, its possible expansions, and the detailed data of existing productions should be considered. The goal of economic efficiency should not only be achieved by optimizing production processes but also by planning the building structure and equipment [10]. Typically, the production design and the building design occur separately and interact too late so that the building results into a polygonal envelope of the simplified space program [9]. Concerning architecture, the continuous optimization of production and the extensive collection of data regarding utilization and profitability, is in severe contrast to the planning and design of the factory building [9]. Production technology is undergoing increasingly rapid change. The advent of automation and partial automation of work steps has shown that the demands placed on production spaces can change several times during the building's service life [10]. Current *box-in-box* principles are often used as a reaction but require factory constructions with the broadest possible, column-free enclosed space. That is why space shortage and, above all, sustainability and resource economy represent a considerable challenge for contemporary industrial architecture.

It is worth considering what the digitalization and interdisciplinary aspects of the industry have to offer and question the current architectural planning process. This research project pursues an alternative approach, investigating how to integrate evolutionary single- or multi-objective optimizations into the design processes of industrial architecture. The aim is to solve specific design decisions, i.e. production process layout or accessibility of factory spaces, based on the provided data.

1.2 Architecture Optimized by Algorithms

Algorithm-based optimization is one of the technologies used to improve architectural designs. An algorithm could be defined as a set of rules consisting of distinct, finite steps to solve a problem [13]. Supposing one considers the design task a problem of partially contradictory influencing factors, which are in equilibrium in an optimal state, an algorithm can be used to find a potential solution. Optimization principles are implemented by parameters and their relations defined by design factors and constrains. An algorithm-optimized architecture can be archived by solving the problem concerning one or more defined goals by optimizing the parameters. Thus, the design derives from its restrictions and demands on the space. This bottom-up process allows architects to influence the design even without knowing the final shape [1]. By generating solutions that are neither known to the designers nor imaginable for them, a new way of decision-making is created [15] (Fig. 1).



Fig. 1. Differences in decision-making

2 Methodology

In industrial design projects, data is usually available regarding the production process. Within this project's scope that deals with a new type of serial production of natural fiber composite dinghy hulls, this data was established by the author. It consists of an organizational chart showing the various relationships between the production steps and room data sheets. The latter lists the requirements for the production steps as well as room specifications regarding minimum dimensions, operational safety, and work environment.

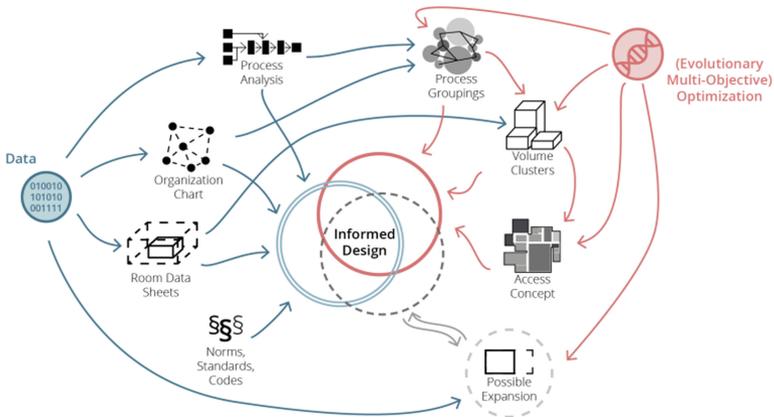


Fig. 2. Diagram of the overall methodology of *informed design*

In order to implement algorithm-based optimizations, a simple translation of design requirements into a single, overall optimization system was not a viable approach. Therefore, the design steps were formulated and dissected to investigate which could benefit from the optimization application.

Figure 2 shows how the data and optimization influenced the so-called *informed design process*. Whether digitally enhanced or not, each design decision formed the basis of the next and most directly made use of the data provided. In this way, the method was sensibly developed from the global to the detail. The aim was to find a method where human design skills and digital tools can work together. The key of the process was to implement specific tools readily available in a transparent way so it can be adapted to other factory design projects.

2.1 Overview of the Design Steps

All optimizations were implemented with the CAD software *Rhinoceros 3D* in the visual programming environment *Grasshopper*. They were partly based on existing plug-ins or, i.e. the volume cluster optimization, explicitly developed for this research (Fig. 3).

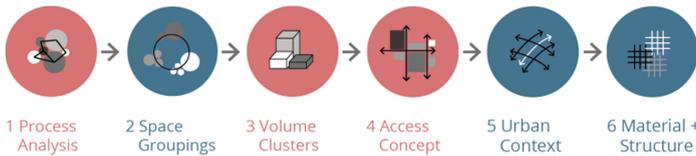


Fig. 3. Design steps. Digitally optimized decision-making steps in red, conventional design steps in blue

Process Analysis. The process structure was developed, employing the *Grasshopper* Plug-In *Syntactic* by Pirouz Nourian, which offered a toolset that generated a function graph via points and lines using a force-based graph drawing algorithm [12]. Production steps and their significance based on the frequency of use and their connection were input into the optimization. The graph was then displayed as a bubble diagram. A catalog summarized the resulting diagram-like solutions to develop a model of the *process structure*.

Space Groupings. Based on the *process organization*, the production steps were manually grouped into areas.

Volume Cluster. This step will be further explored in Sect. 2.2.

Access Concept. Since an efficient production relies on an adequate access concept, the previously generated abstract *volume clusters' arrangement* was optimized. The basis for this optimization was the *Grasshopper* Plug-In *Magnetize*, a project by Egor Gavrillov, which creates an optimal corridor system that links rectangular, two-dimensional spaces based on previously specified, necessary relations between said spaces [4]. The footprints of the abstracted *volume clusters* were arranged by the optimization and provided with optimal access. The generated floor plans were analyzed to form rules, which were then applied to the design.

Urban Context. Intuitive but informed decision-making strategies were used to situate the building in the urban context. For this purpose, all findings from the design steps and the SWOT analysis were consulted. By combining these principles, an overall cluster was produced, which can function as the starting point of the formulation.

Material and Structure. The final step was the design of the construction and the choice of materials. Following the project, which focuses on resource-saving boat building, sustainable materials were prioritized. Often, however, the function of the room determines the materials used.

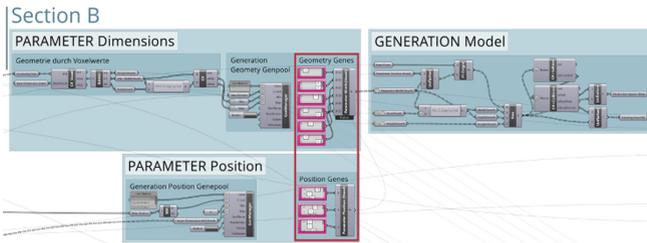


Fig. 6. Section B. *Volume clustering optimization script in Grasshopper/Rhinoceros 3D*

The model of the production spaces was generated using the genes. This was scripted using an iterative method of first sorting the boxes decreasingly by volume and then stacking them on top (Fig. 7).

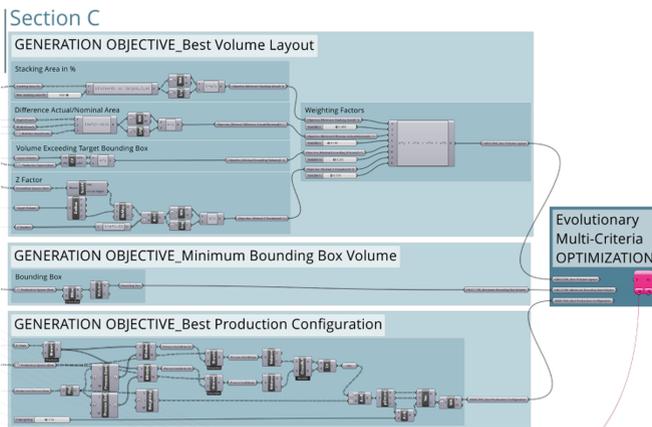


Fig. 7. Section C. *Volume clustering optimization script in Grasshopper/Rhinoceros 3D*

From this model, the three target values were then determined in Section C, towards which the optimization was aimed. The *best volume layout* objective pursues the most realistic stacking and arrangement of the voxel volumes. It is obtained by adding the normalized and weighted values of several factors, such as the *minimum stacking area*, the volume exceeding the *target bounding box*, the *preferred proximity* of the space to the base plane, and the *actual and nominal footprint difference*.

The objective *minimum bounding box volume* numerically represents the size of the bounding box of the generated volume. The objective *best production configuration* represents the sum of the distances of the connections between spaces, weighted by their priority. The evolutionary optimization *Octopus* was executed to manipulate the given gene pools to minimize the target values. After generating the first population of solutions, the following child generations were subsequently derived through selection, crossing, and mutation.

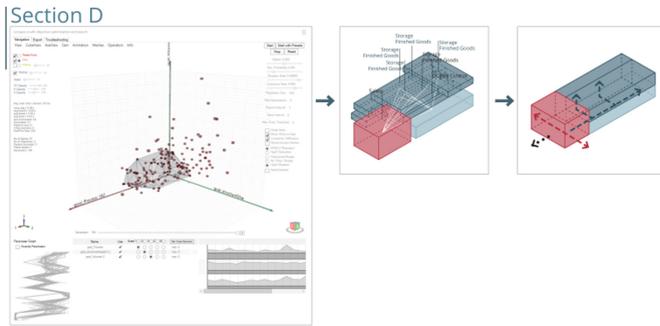


Fig. 8. Section D. *Volume clustering optimization in Octopus/Rhinoceros 3D*

In Section D (Fig. 8), a pool of solutions was created by repeating the optimization for a sufficient number of generations. The best solutions were analyzed by using the *pareto* mesh of the three objectives. The individual final clusters and their iterations were examined for their functional principles of spatial arrangement, e.g., vertical stacking or prefixed volumes. Finally, these principles or arrangement schemes were incorporated into the design.

3 Results

This research project integrates algorithm-based optimizations into the design process of an exemplary industrial architectural project to improve the coherence of the production and the factory building. Using the developed design method, an arrangement of symbiotic production rooms in the final architectural design was achieved, providing proof of concept.

Figure 9 (left) shows the design decisions derived from either data processed by optimizations or conventional design techniques. The diagrams on the right display retrospectively the influences of these decisions on the final structure. The results, as shown in Fig. 9, indicate that the production of the factory and its form are connected within all the design steps.

4 Discussion and Future Development

The results indicate the benefits of defining precise design steps and applying optimizations if suitable. Compared to the conventional process, the proposed system is able to utilize an extensive amount of data provided to improve the outcome. It is possible to generate relevant results, even for design problems with contradicting factors.

The effectiveness of the suggested method stems from its adaptability. Contrary to many concepts in parametric design, this approach can handle complicated and straightforward problems. By breaking the design task down into steps, the problem can be simplified, and the solutions can individually be implemented into the design process.

The presented design method developed in this case study should be understood as a guideline, as it was not intended to create a design generation tool. A proper application

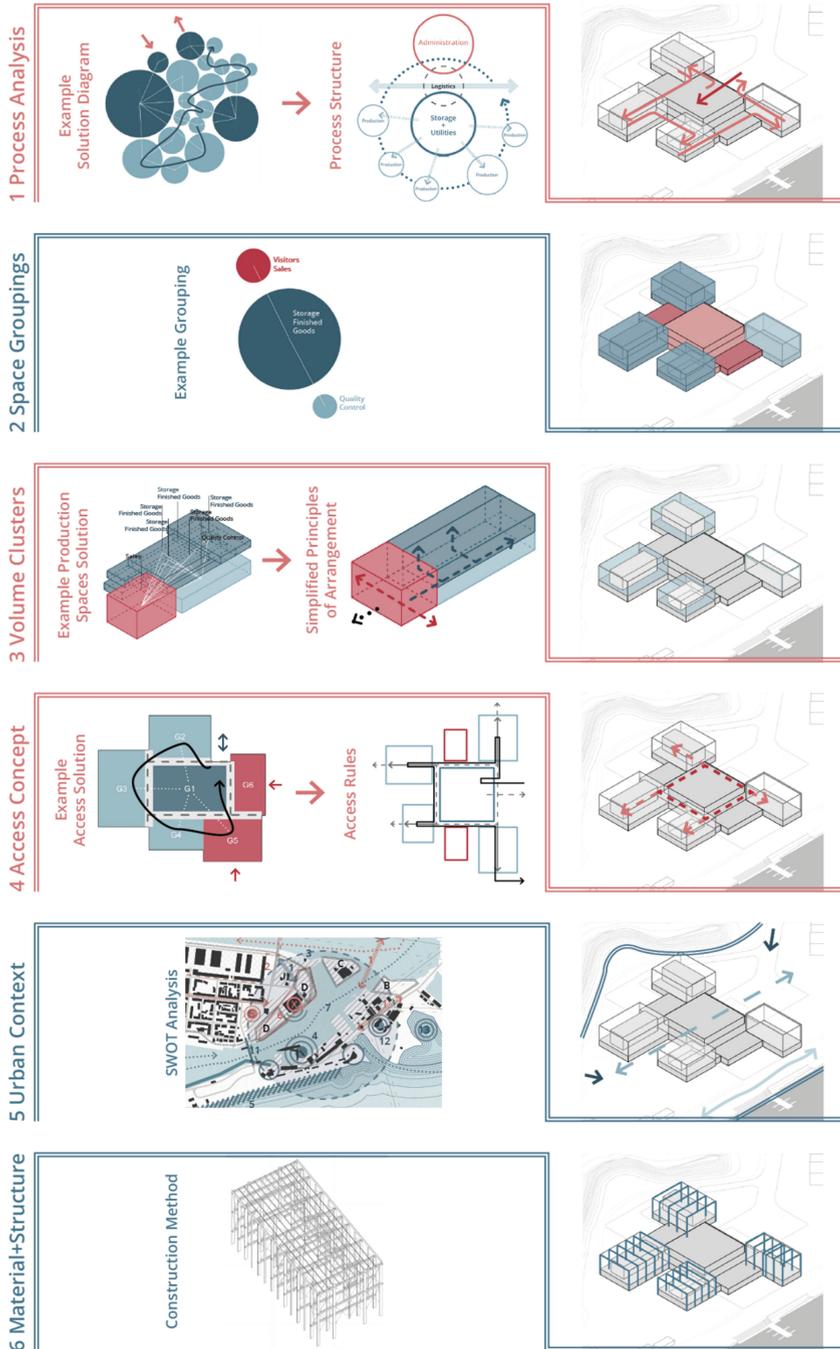


Fig. 9. Results of the design steps and their representation in the final design. Digitally optimized decision-making steps in red, conventional design steps in blue

of optimizations can only be recommended if the limitations and operating methods are known and not hidden as a *black box* application. The abstract logic inherent in technologies such as optimizations can promote and improve conventional design, as long as their use is transparent and plausible.

Another interesting benefit is the possibility of using the design structures after completion of the planning or construction. An evaluation of built designs through their designing factors could provide crucial information of performance and degree of capacity utilization. This could become a *digital twin* of the functioning, making projections for expansions or restructuring more precisely.

5 Conclusion

As parametric design has proven to be valuable and effective after years of practical use, optimization should be applied more often in industrial architecture. Optimized and conventional design steps should not be seen as contradictory or in competition with each other. Instead, their differences offer opportunities to tackle problems in different ways. The outcome of this project shows that they work particularly well in combination.

This new design process could be an essential element for responsible and sustainable factory planning. In today's age of information, optimizations offer technology that, using available data, could solve the complex problems of resource-efficient building and should therefore be investigated further.

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