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Interactive design with optimum matchmaking of reused structural elements – a software implementation

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Abstract

Structural systems are a significant contributor to buildings' embodied carbon and reusing structural elements in new load-bearing applications is one strategy to reduce this impact. However, integrating this approach into existing design workflows without affecting design freedom is challenging. New computational tools like Phoenix3D, a plugin for Grasshopper within the Rhino3D environment, are intended to help master this task. This paper extends current research developments of Phoenix3D by integrating the tool into a more flexible multi-objective optimization framework. Hence, the outcomes obtained from Phoenix3D are employed as an objective function in the optimization workflow. This enables designers to move from a mere assignment operation on a predetermined structural system to a more comprehensive approach, wherein alternative design options are thoroughly investigated. Two case studies are conducted here to showcase this extension's effectiveness: (1) a theoretical study that compares generated designs with established typologies; and (2) a real-world application of the proposed tool to design a façade system using only reclaimed steel elements. Results show that adequate design solutions are found in real-time and interactively for the same stock of reused structural elements. Not only does Phoenix3D turn component reuse constraints into new circular design opportunities, but it also reduces the detrimental environmental impact of a structure and therefore allows the establishment of a more sustainable building culture.

Keywords: computational design, interactive design, optimization, reuse, circular design

1. Introduction

The construction industry is responsible for substantial global greenhouse gas emissions, resource exploitation, and waste generation [1]. To mitigate these adverse effects and decrease the detrimental environmental impact (DEI) of constructed buildings, one possible solution is to adopt a circular economy approach, which involves reusing structural components to construct new buildings.

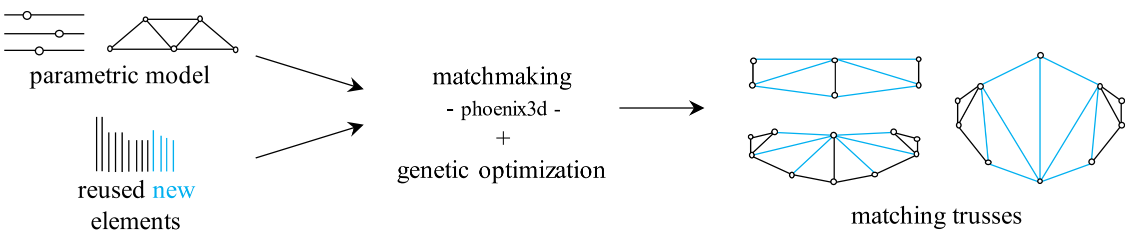

Figure 1. Matchmaking of truss structures for a given stock of reused and new elements

With a few exceptional cases, this approach is not commonly used in current building practices. One of the reasons for this is that reusing structural components demands an inversion of the conventional design approach, as the synthesis of a structural system (including topology and geometry) must comply with the geometric and static characteristics of the available elements. As a result, this leads to challenges in the regular construction process. One solution to this issue is using computational tools that assist architects and engineers when designing from a fixed inventory of elements. An early approach of such computational tools was presented by Fujitani and Fujii [2], who optimized plane frames of fixed topology subject to given elements of known length and cross-section. Kim and Kim [3] used genetic algorithms to optimize embodied carbon, weight, and cost of frame structures made from a stock of reclaimed elements. Bukauskas et al. [4] developed a strategy based on heuristics to form-fit a supply of wood logs to statically-determinate trusses. Brütting et al. [5] presented structural optimization techniques based on mixed integer linear programming (MILP) to design truss and frame structures from reclaimed steel elements. Huang et al. [6] employed the Hungarian Algorithm to design wooden geodesic domes from a stock of elements. Additionally, they briefly compare various algorithmic formulations for reuse-driven design in computational tools. In previous work, Warmuth et al. [7] introduced the computational tool **Phoenix3D** which optimally assigns reclaimed and new elements from a given stock to target truss designs. This tool was built upon a MILP formulation and was later extended with a Best-Fit heuristic to accelerate result generation.

To further open up the design possibilities of stock-constrained design, this paper introduces an extended method to generate design alternatives when working with a given stock of elements. Rather than solely assigning stock elements to a pre-defined structural system, this method enables interactive design with the available stock components. The method's general workflow is depicted in Figure 1. The input consists of a parametric model and a stock of both reclaimed and new elements, which are fed into an optimization framework. This framework utilizes a combination of Phoenix3D and genetic optimization algorithms to modify the parametric model and to optimally assign stock elements to the design. As a final step, the framework produces several truss structures that make optimal use of available stock elements. Section 2 elaborates on the algorithms of Phoenix3D and the genetic optimization process. Furthermore, Section 3 features a theoretical case study that compares generated structures with established typologies and a real-world project that illustrates the practicality of this framework.

2. Method

2.1 Phoenix3D

Phoenix3D is an open-source tool to design optimum truss structures made from a stock of new and reclaimed elements. In the tool, the assignment of stock elements to a design brief is formulated as a discrete optimization problem.

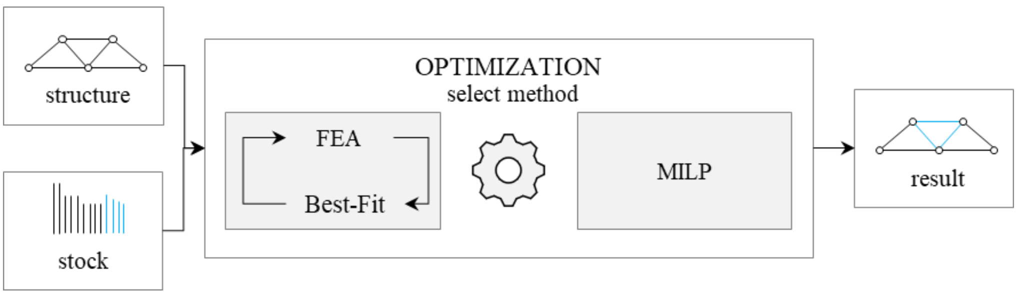

Figure 2. Workflow of Phoenix3D

It is implemented by the authors based on previous research in the field [6]. The core of Phoenix3D is molded by two optimization algorithms: (1) a MILP formulation that delivers globally optimal results but is computationally expensive, and (2) a Best-Fit heuristic combined with a linear-elastic finite element analysis (FEA) of first order that delivers just close-to-optimal results but in real-time and with low computational costs. The objective function is to minimize DEI, computed by a Life-Cycle-Assessment (LCA). Details for the implementation of the optimization algorithms as well as the LCA, can be found in [7, 8]. The workflow of the tool is illustrated on Figure 2. An initial structure serves as input to which reusable stock elements are assigned, as well as newly-manufactured elements. Subsequently, users can select which of the two optimization algorithms should be employed to assign the stock elements to the structure optimally. As a result, the structure with the assigned stock elements is displayed, including statistics about the run optimization. Among these are the DEI in kgCO_2eq and the cut-off waste in kg. Cut-off waste occurs when reclaimed elements from the stock must be cut to fit a target position in the intended design. In general, it is worthwhile to minimize the amount of cutoff waste and employ reclaimed elements as they are to enable an additional cycle of repurposing.

2.2 Global optimization framework

As outlined in Section 1, the proposed framework employs a genetic optimization algorithm to produce trusses that match a given stock of reclaimed elements. The overall workflow is illustrated on Figure 3, which starts with the definition of a parametric model. For the case study in Section 3.1, the parameters, i.e. the design variables, include the number of bays, the direction of diagonals, and the nodal coordinates of the design brief. A stock of reclaimed and new elements is provided, all made of steel S235. Furthermore, various circular cross-sections are available, with both reclaimed and new elements ranging from diameters of 10 mm to 100 mm with steps of 10 mm in between. For each cross-section of reclaimed elements, six pieces of length 3.0 m are available.

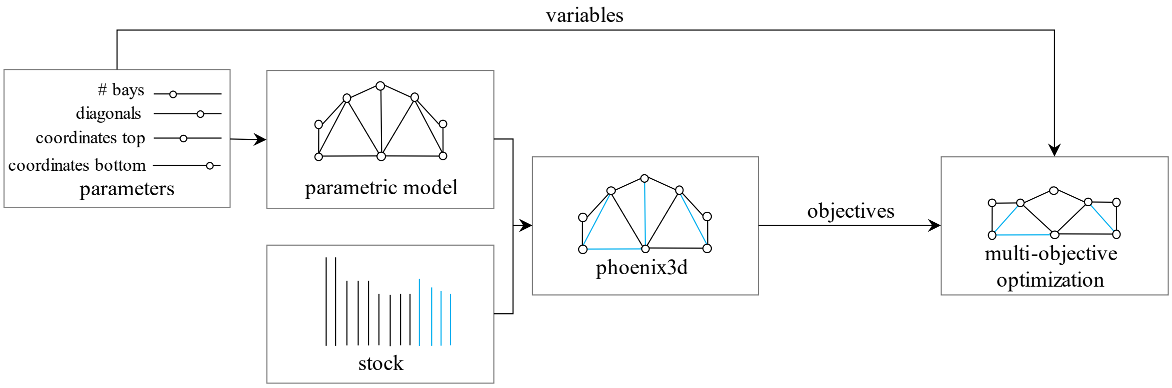

Figure 3. Workflow of the presented framework

Despite Phoenix3D's ability to optimally assign stock elements to an already specified structure, modifying the topology and geometry of the design brief opens up the solution space by allowing the design to adjust to the characteristics of the reclaimed elements from the stock. Since the model is parametric, this can also be regarded as an optimization problem where the model's parameters serve as design variables, and the calculation of DEI and cut-off waste in Phoenix3D act as objective functions to be minimized. Wallacei [9], an evolutionary optimization and analytic engine for Rhino/Grasshopper [10], is the primary tool for this overarching optimization.

3. Case studies

3.1 Theoretical case study

The theoretical case study setup is illustrated on Figure 4. The design boundaries in which the parametric truss is generated are presented on Figure 4a. To simulate a loading scenario, a line load of 15 kN/m is assumed, and the self-weight of each bar is applied at its respective end nodes. In addition, Figure 4b displays a benchmarking truss optimized by employing the Best-Fit heuristic to minimize DEI solely. Three well-known truss typologies, a Warren truss, a Pratt truss, and a Howe truss, are shown in Figure 4c. The corresponding metrics for these trusses, such as their DEI in kgCO_2eq and their cut-off waste in kg, are given in Table 1.

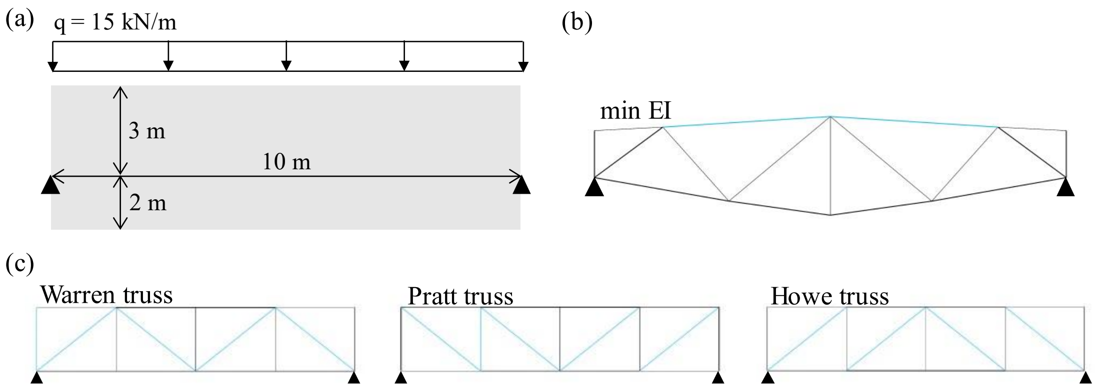

Figure 4. Matchmaking of well-known trusses with optimal trusses for minimization of DEI

Table 1. Results for the trusses from Figure 4

	min DEI	Pratt truss	Howe truss	Warre n truss	(5a)	(5b)	(5c)	(5d)
DEI [kgCO_2eq]	41	83	67	70	55	46	44	43
Cut-off [kg]	8	27	18	17	0	1	2	4

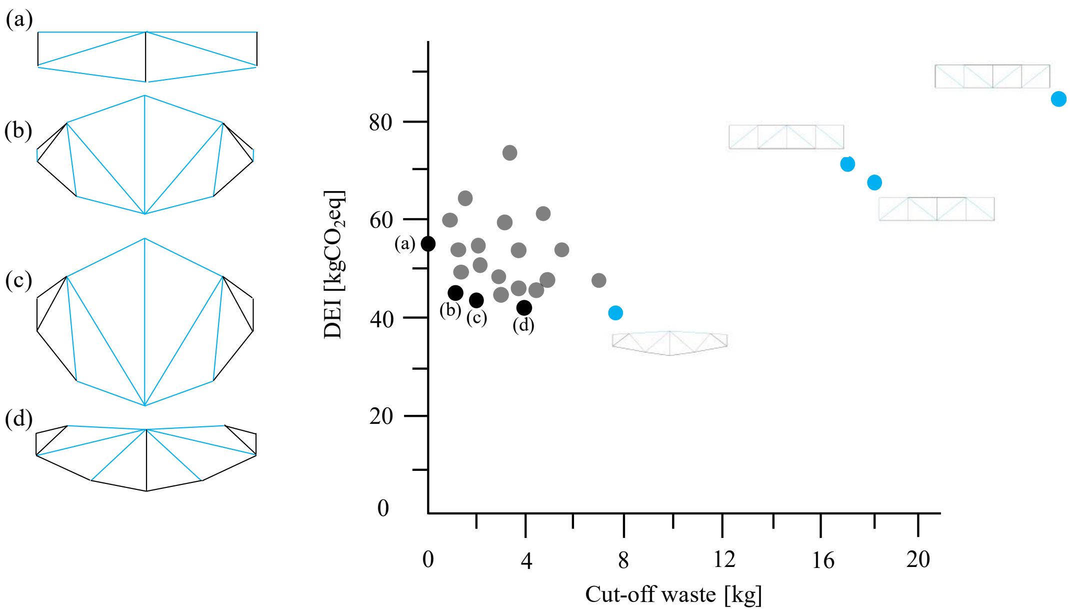

Figure 5. Pareto front with selected samples subject to the minimization of DEI and cut-off waste

Table 1 shows that the benchmark DEI is 41 kgCO_2eq, which results in a cut-off waste of 8 kg. The three truss structures have DEI values ranging from 67 kgCO_2eq to 83 kgCO_2eq and also generate significant amounts of cut-off waste, ranging from 17 kg to 27 kg. The goal of the optimization is to generate truss structures that are more suitable for the given stock, with the ability to reduce cut-off waste and ideally outperform the three standard trusses in Figure 4c in terms of DEI. Therefore, a multi-objective optimization is set up for two objective functions: minimizing DEI and cut-off waste. Selected results from the multi-objective optimization are presented on Figure 5. The Pareto front of the optimization is represented by black dots, non-optimal solutions by grey dots, and the trusses in Figure 4 by blue dots. The four Pareto-optimal solutions (Figure 5a-d) are displayed to the left of the graph. As shown in Table 1, all generated trusses have a significantly lower DEI than the three trusses in Figure 4c, ranging from 43 kgCO2eq to 55 kgCO2eq. Moreover, their cut-off waste ranges from 0 kg to 4 kg, indicating that the identified solutions are more suitable for the stock than the initial truss structures.

3.2 Façade Primeo Energie Kosmos

The real-world project presented in the following involves designing and constructing the façade for the Primeo Energie Kosmos in Münchenstein, Switzerland. The design intent was to obtain a tree-like façade structure of complex geometry. Reclaimed steel elements from obsolete electric masts were to be used, which had already been dismantled and inventoried.. The available stock contains 1’361 linear elements with a total length of 4’329 m ranging from 1.4 m to 6.2 m. Figure 6 shows a scatter diagram of the in total 125 different stock element groups.

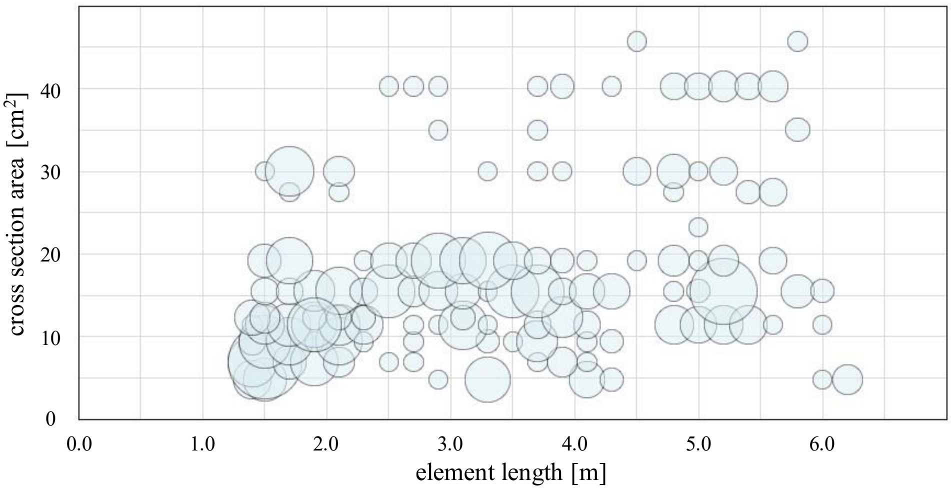

Figure 6. Stock composition

Most elements are either circular hollow sections or L-sections, an excerpt of which is pictured on the top left of Figure 7. In the following step, the available inventory was imported into Phoenix3D to be used for the assignment optimization. After applying the method described in Section 2, a range of design variations was generated; the eventually selected one is shown at the bottom left of Figure 7. Following several iterations, the final solution was established. An added advantage of working in the Rhino/Grasshopper environment was that detailed component drawings could be generated automatically, which could be directly delivered to the steel fabricator. The construction of the façade was completed in fall of 2022, Figure 7.

Figure 7. Realized facade system based on the proposed method

4. Conclusion

This paper introduced an extended framework for the reuse-driven design of structural systems based on the parametric design tool Phoenix3D for Rhino/Grasshopper in combination with a genetic multi-objective optimization algorithm. A theoretical case study has been developed to generate different design alternatives from one stock of structural elements. Moreover, the framework was used to design a real-world application, the façade of the Primeo Energie Kosmos in Münchenstein, Switzerland.

Regarding design flexibility, future investigations will further expand the range of applicability to frame structures. Moreover, the developed Best-Fit heuristic will be improved to generate more accurate results when compared with a MILP-based implementation. This allows for more real-world applications and emphasizes integrating reuse strategies into conventional structural design workflows.

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