World Conference on
Timber Engineering
Oslo 2023

REUSE OF LOAD-BEARING TIMBER ELEMENTS – CASE STUDY OF A LOOKOUT TOWER IN LAUSANNE, SWITZERLAND

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ABSTRACT: The construction industry is jeopardizing Earth's environment; current mitigation efforts do not suffice; and additional sustainable strategies are required. One such strategy consists of reusing structural building elements over multiple service lives. In this context, this paper introduces a new framework for the design of timber structures made from reused structural elements. Beyond general approaches to reuse structural elements, the proposed framework provides a computational approach that supports architects and engineers in their design and decision making. In this course, optimization techniques such as Best-Fit heuristics are implemented to optimally utilize available stock elements in a new design. The introduced framework is applied to a real-world case study where a lookout tower is designed from timber elements salvaged from a soon-to-be-demolished lookout tower. Results show that a new design that makes optimal use of available stock elements and that meets architectural and statical requirements exists. In the long run, the introduced framework for the reuse of structural elements encourages the design of more sustainable structures with lower environmental impact.

KEYWORDS: Reuse, Structural Design, Computational Design, Life Cycle Assessment, Circular Economy

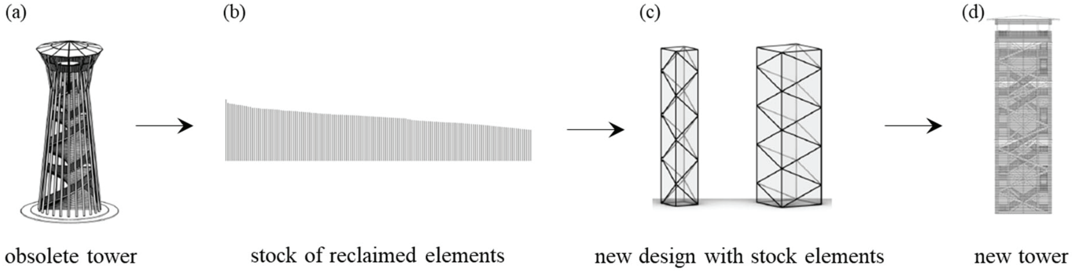

Figure 1. *Conceptual workflow for the design of a new lookout tower made from reused elements*

1 INTRODUCTION

The construction sector is responsible for a significant amount of global greenhouse gas emissions, resource exploitation and waste generation [1]. One way to remediate this detrimental condition and to reduce the environmental impact (EI) of built structures is the introduction of a circular economy and, associated with that, the reuse of structural elements in new structures. Apart from a few unique examples, however, this approach is rather the exception in today's building practice. The reason for this is that the conventional design approach is inverted in the case of reusing structural components, as the synthesis of a structural system (including topology and geometry) must comply with the geometric and static characteristics of the available elements. Consequently, this leads to challenges in everyday construction. One solution to this challenge is the use of computational tools, that make use of algorithmic formulations to assist the design with a fixed inventory of elements. An early computational approach was presented by Fujitani and Fujii [2] who optimized plane frames of fixed topology subject to given elements of known length and cross-section. Brütting et al. [3] presented structural optimization techniques to design truss structures from reused steel elements. Regarding timber, Bukauskas et al. [4] have developed a strategy based on heuristics to form-fit a stock of wood logs to statically-determinate trusses. Amtsberg et al. [5] presented a design-to-fabrication workflow using a geometric matching algorithm that makes best use of available tree forks. Huang et al. [6] employed the Hungarian Algorithm to design wooden geodesic domes from a stock of elements. Moreover, they provide a comparison of different algorithmic formulations for reuse-driven design in computational tools. In previous

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https://doi.org/10.52202/069179-0469

work, Warmuth et al. [7] introduced a computational tool subject to support architects and engineers in designing structures with reused elements. This tool was built upon a mixed-integer-linear-programming (MILP) formulation to optimally assign stock elements to a given structure and was later extended by a Best-Fit heuristic to accelerate result generation. Their studies centred around the evaluation of steel and concrete as reusable materials. In this paper, the range of applicability is extended to timber structures, and the computational techniques from [6, 7] are implemented into a novel framework that allows for the design of timber structures made of reused elements in a flexible, interactive, and designer-driven workflow. The extension is demonstrated via a real-world case study, the new design of a lookout tower in Lausanne, Switzerland, made from an already existing tower on-site that became obsolete. Figure 1 shows the conceptual workflow for this: first, structural elements from the obsolete tower (Fig. 1a) are assessed and inventoried into a stock of elements (Fig. 1b). Then, a new design is developed based on the characteristics of the obtained stock (Fig. 1c) that leads finally to a new tower making optimal use of the available elements (Fig.1d). As per previous research on the topic [9, 10], it is expected that this significantly lowers the EI of the tower, the demand for resource mining, and waste production, compared to one built of new elements.

2 REUSE OF TIMBER

The goal in a circular economy is to maintain material, product, and components at their highest value for as long as possible. In case of timber, the amount of CO_2 emitted during combustion is equal to the amount absorbed by the plant during its growth, making timber a useful carbon sink [11]. In addition, reusing timber prevents its decomposition under anaerobic conditions, which would lead to the release of methane and contribute to greenhouse gas emissions [12]. And thanks to dismountable connections, timber structures are generally presenting high potential to be reused. Despite all these valid reasons to reuse timber, component reuse, regardless the material, is not the norm in building practice. The reasons for that are manifold. Conventional demolition processes tend to yield very little reusable material due to the use of heavy machinery. Reclaiming such material implies to process a meticulous disassembling of the structure that, as expected, has an impact on costs. However, Schultmann et al. [13] illustrate that environment-friendly dismantling and reuse strategies can even be advantageous from an economic point of view. In response to demolition costs, reusing timber has very variable cost implications, from cost savings of up to 80% depending on application and quality [14]. To ensure a safe reuse of timber components, their mechanical properties need to be assessed. In addition to natural aging phenomena of wood and duration of load, the presence of mechanical damage and biological attack must be considered. Although researchers seem to agree that aging has no, or only marginally, effects on bending capacities, the duration and intensity of the applied load have a direct effect on the material properties [15] and are known to cause strength reductions on a logarithmic scale [16]. The direction of loading should also be considered when assessing the remaining mechanical properties of reclaimed timber. Nevertheless, laboratory tests by Brol et al. [17] on 130 year old timber elements indicate that elements which worked as beams for many years can still be integrated in new structures as elements with axial loading. Moreover, Davis [18] states that timber is resilient over time and maintains much of its original capacities despite the effect of moisture, loading, temperature, and weathering [18]. And still, despite all these promising indicators to reuse timber, this strategy is rarely pursued today, albeit this was not always the case in the past. Küpfer & Fivet [19] state that dismantling timber structures and reusing their components were common practice before the Industrial Revolution. But due to new means of production and transportation, the common reuse and valorisation techniques were progressively abandoned. An example on how timber was reused in the past is shown in Figure 2.

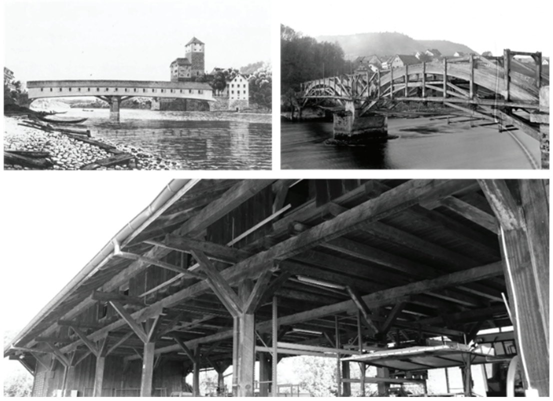

Figure 2. *(Top left) timber bridge from 1810, (top right) deconstruction in 1919, (bottom) new barn built in 1920 and still in use*

On the top left, a bridge can be observed that was built in 1810 in Eglisau at the German Swiss border to cross the river Rhine. After more than 100 years in service, it was decided to deconstruct it in 1919 due to a water level elevation of the river. Instead of landfilling its components after deconstruction, a new barn in Rheinhau, Switzerland, was built in 1920 from components of the deconstructed timber bridge. The barn is still in use and in good condition. The building is more than 100 years old but made from oak and spruce components that are over 200 years old. This simple illustration effectively demonstrates the mentality necessary for material-caring building practices.

3 DESIGN METHODOLOGY

The main objectives of this paper are (1) to introduce a new design framework and (2) to develop a case study i.e., the design of a load-bearing structure for a timber lookout tower made of reclaimed elements. Again, it should be noted that the design of structures with reused elements from an available stock inverts the conventional design process. Typically, the structural layout determines the required elements to be manufactured. Instead, the design of structures through reuse describes the inverse: structure topology and geometry must be designed to make the best use of available stock elements. To achieve this goal, the workflow shown in Figure 3 is employed.

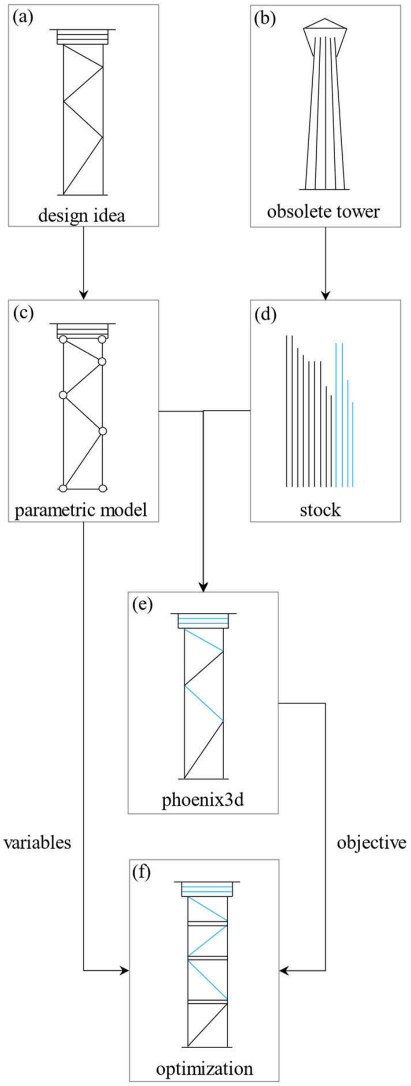

Figure 3. *Workflow of the introduced framework with new elements (blue) and reused elements (black)*

First, an initial design idea is conceptualised either by a hand sketch or a digital drawing (Fig. 3a). Based on this, a parametrized design model is created (Fig. 3c). In parallel, the source material from the obsolete tower (Fig. 3b) is identified and assessed. Once assessed, the stock of reused and new elements can be inventoried (Fig. 3d) where reused elements come from the obsolete tower and new elements are assumed to be available from new production. Assigning available stock elements to the parametric model such that the stock is utilized optimally is a time-consuming task when done by hand. Therefore, the computational tool Phoenix3D (P3D) [20] is assigned this process (Fig. 3e). P3D takes both the stock and parametric model as an input and returns the model with optimally assigned stock elements subject to minimize upfront global warming potential of the structure manufacturing. Finally, a global optimization process (Fig. 3f) modifies the set of variables of the parametric model such that the configuration with the least EI is found. More details of each step are given in the following sections.

3.1 PARAMETRIC MODEL AND STOCK IDENTIFICATION

The computer aided design software Rhino3D [21] is used to set up the parametric model. Included in Rhino3D is the visual programming plugin Grasshopper that takes care of the parametrization of the design idea. This allows a fast alteration of the design idea. Before setting up the parametric model, some constraints for the design have to be taken into account. For reasons of rationality, it was decided to allow only rectangular geometries. Moreover, the loadbearing structure is considered to be made of two sub-structures: an inner and outer truss. Furthermore, a tower height of at least 30 m is chosen to ensure a 360° panorama view, since the trees surrounding the tower have approximately this height. Within these constraints, the model can be created.

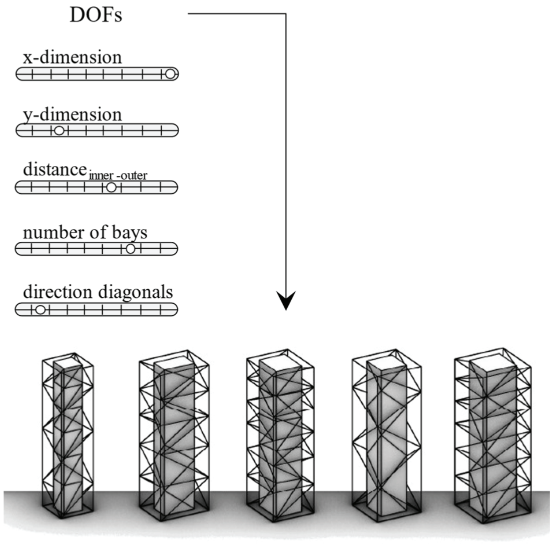

Figure 4. *Various tower configurations within the parametrization*

When setting up a parametric model, parameters, so called degrees of freedom (DOFs), have to be chosen. Ideally, the quantity of DOFs should be controlled in such a manner as to avoid losing control of the model, yet still allow for sufficient modification. The degrees of freedom chosen in this case study are shown in Figure 4 and consist of the x- and y-dimension, the distance between inner and outer truss, the number of bays, and the direction of diagonals. In order to reuse structural elements and to employ P3D, a stock needs to be set up. This stock contains both reusable elements that were sourced from the obsolete tower (discussed specifically in Section 4.3) and elements that were newly produced. Reused elements have to be assessed for their mechanical and geometric properties. To retain the degree of complexity in this investigation, it is assumed that all available new elements are of same cross-section as available reused elements. Moreover, for new elements, only mechanical properties are taken into account because they can be provided in customized lengths.

3.2 STOCK ASSIGNMENT BY PHOENIX3D

The assignment of stock elements to the design model is here described as a discrete optimization problem and is carried out by P3D. P3D is an open-source tool to design optimum truss structures made from a stock of new and reused elements. It is implemented by the authors based on previous research in the field [8]. The core of P3D is moulded 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 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 EI which is computed by a Life-Cycle-Assessment (LCA). Details for the implementation of the optimization algorithms as well as the LCA can be found in [6, 19]. Figure 5 shows the workflow of the tool.

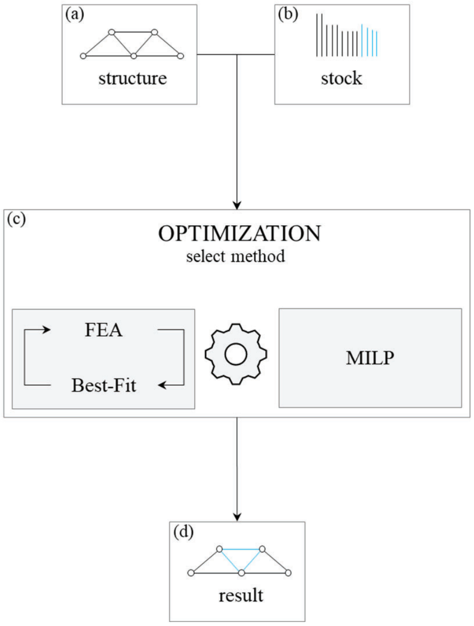

Figure 5. *Workflow of the computational tool Phoenix3D*

An initial intended structure serves as input (Fig. 5a) to which reusable stock elements are assigned as well as newly-manufactured elements (Fig. 5b). Subsequently, users can select which of the two optimization algorithms should be utilized to optimally assign the stock elements to the structure (Fig. 5c). As an output, the structure with the assigned stock elements is displayed (Fig. 5d) including statistics about the run optimization. Among these are the EI in [kgCO_2eq] and the percentage of reused and new elements in the structure, which will be used in Section 4 to assess the case study.

3.3 DESIGN OPTIMIZATION

Although P3D already optimally assigns stock elements to a given structure, the structure geometry itself can be modified as well to better fit to available stock elements. Thanks to the parametric implementation of the model, this can also be described as an optimization problem where the parameters of the model are serving as design variables and the computation of EI in P3D serves as an objective function (see Fig. 3). The tool used for this optimization is Wallacei [22], an evolutionary optimization and analytic engine for Grasshopper. Besides the objective of minimizing the EI, there are other factors that need to be taken into account. One is to utilize the available stock elements from the obsolete tower as much as possible because they would become waste otherwise. Another constraint considers aesthetic aspects of the design, which are evaluated by the designer. The compliance of these constraints is evaluated by the designer and therefore not subject of the optimization process. This means, however, that several iterations are necessary to end up at the final solution.

4 RESULTS: DESIGN OF THE SAUVABELIN TOWER IN LAUSANNE

In the following, results for a new design of the Sauvabelin lookout tower in Lausanne, Switzerland, are explained using the methods described in Section 3. Figure 6 shows the 20-year-old tower, now obsolete and in need of replacement.

Figure 6. *The Sauvabelin tower, October 2021*

For the case study, only the structural system is taken into account. However, it is aimed to apply common rules of

https://doi.org/10.52202/069179-0469

best practice for timber structures. This includes the protection of exposed elements from weather as well as homogeneous connection designs for constructive and economic reasons.

4.1 INTRODUCTION TO THE SAUVABELIN TOWER

In order to produce a viable project that addresses structural, architectural, societal, and environmental considerations, it is crucial to understand the importance of the existing tower. The Sauvabelin lookout tower was constructed in 2003 and since then has become a renowned landmark in the city of Lausanne located on the shores of Lake Geneva. Figure 7 depicts the tower during its construction phase. The overall concept encompasses a spiral staircase culminating in a viewing platform at its apex.

***Figure 7.** Construction of the tower, 2003*

The Sauvabelin Tower, despite its popularity and emotional resonance among the residents of Lausanne, is slated for demolition due to considerations of safety and economy. The estimated service life was originally predicted to be 20 years. However, this projection of service life does not necessarily equates to the end of its structural components' service life. With proper maintenance and restoration, it is possible to extend the service life of the tower. Thus, between the years 2012 and 2017, the tower underwent maintenance work that involved the replacement of defective components. Figure 8 illustrates the replacement of the stair ends that were weathered.

***Figure 8.** replacement of end parts of the stairs*

It is projected that the costs associated with maintaining the structure will continue to rise as the tower ages and reaches its revised estimated service life of 30 years in 2033. However, due to the design of the tower's structure, the maintenance costs would eventually surpass their limits, resulting in the tower's demolition. A potential solution to this scenario is to disassemble the tower now, salvaging its structural components that are still in good condition, and use them to construct a new tower that adheres to construction standards that prevent the elements from causing premature aging.

4.2 EXPLANATION OF AVAILABLE STOCK ELEMENTS

The stock of salvaged elements for this case study involves an evaluation of the current state of all structural components of the existing tower. The evaluation of the structural elements was conducted in September 2021 and was based on a visual inspection of the tower as well as information obtained from the original construction plans. As illustrated in Figure 9, the tower can be segmented into four categories of structural elements: the stairs, poles, stands, and roof. Each category is subjected to an individualized evaluation to determine its viability for reuse.

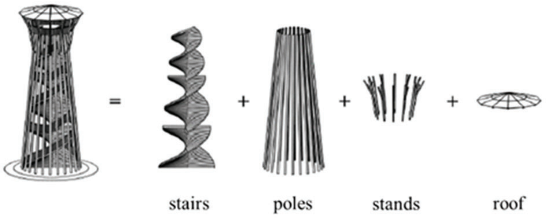

***Figure 9.** Composition of the Sauvabelin tower*

The composition of the tower is comprised of 214 m^3 of timber, of which 141 m^3 are Douglas Fir and 73 m^3 are Spruce, sourced from nearby forests. The exact metrics can be viewed in Table 1.

***Table 1.** tower composition*

	Stairs	Poles	Stands
Species	Douglas fir	spruce	Spruce
Amount	151	24	24
Cross-section	20/40cm	20/20cm	20/20cm
Length	6.0-12.0m	34.0m	8.0m

The tower's staircase comprises 151 steps, which range from 6.0 m to 12.0 m, with a linear distribution in between, and have been assigned a grade of C24 based on the Swiss construction code. It was found that, due to the maintenance work from 2012 – 2017, all steps can be reused, albeit in a different static configuration. As previously mentioned, research conducted by Brol et al. [17] has shown that reused timber elements can withstand a change in the direction of applied loading from bending to axial stress, which would apply to the proposed truss system in this case study. The tower features 24 poles forming its outer finish, however, due to their exposition and the presence of numerous metal connections that weaken their cross-section, these elements have been excluded from this study. The roof, which has a diameter of 13.0 m and is comprised of elements with varying lengths and cross-sections, is in good condition and could be reused in its entirety. For the sake of simplicity and consistency, the decision was made to reuse only the staircase elements, which is the reason why the stands are also excluded, although they are in good condition and could potentially be reused.

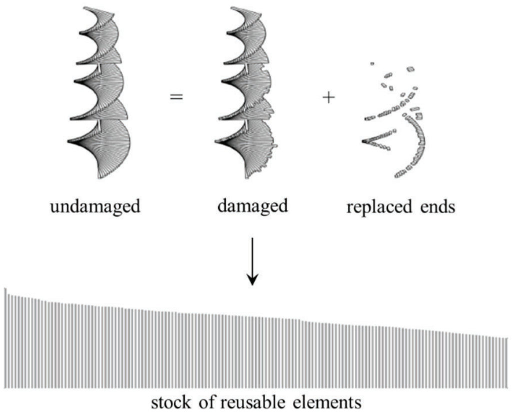

Figure 10. *Extraction of reusable elements from staircase of obsolete tower*

Figure 10 depicts the inventory of refurbished staircase elements that were installed during the previously mentioned maintenance work on the tower. The full stock comprises therefore 151 elements with a cross-section of 20/40 cm and varying lengths between 6.0 m to 12.0 m which results in a total stock mass of 54,319 kg considering a density of 530 kg/m^3.

4.3 DESIGN PROCESS AND FINAL RESULT

As outlined in Section 3, the goal of this case study is to reuse as many stock elements as possible to prevent them from being disposed in a landfill, while keeping the EI low.

Table 2. *results of iterations for tower design*

Iteration [-]	EI [kgCO$_2$eq]	Reused [kg]	Usage [%]
0	14,521	29,177	54
1	15,127	30,648	56
2	14,994	29,993	55
3	14,365	29,187	54
4	14,349	29,201	54
5	15,055	29,679	55
6	14,346	20,193	54
7	19,813	40,370	74
8	21,842	44,782	82
9	22,137	44,771	82
10	22,061	44,781	82
11	24,889	51,164	94
12	30,505	52,373	96
13	**24,564**	**49,504**	**91**
newly made	44,452	0	0

Although minimizing EI is a factor in the design process, it is not the only deciding one, i.e., designs with higher EI than other solutions may still be selected as the final design, as long as the EI is lower than a comparable tower made entirely of new components. Design decisions must balance construction and economic practicality with the aim of minimizing the EI of the structure, while considering personal design preferences. By employing the methods explained in Section 3, numerous suitable designs were found. The chosen designs were selected based on the designer's preferences and are listed in Table 2, including their EI in kgCO$_2$eq, weight of reused elements in kg, and the percentage of utilized stock elements. This usage is calculated by dividing the reused elements in kg by the total amount of reusable elements in kg, with the assumption that the difference is discarded and therefore waste. In Figure 11, the selected designs are represented on a graph, with the EI of the design shown on the vertical axis and the utilization of the stock on the horizontal axis. This visual representation shows that the optimal designs are located in the bottom right corner of the graph, where both a low EI and a high utilization of the stock elements are achieved.

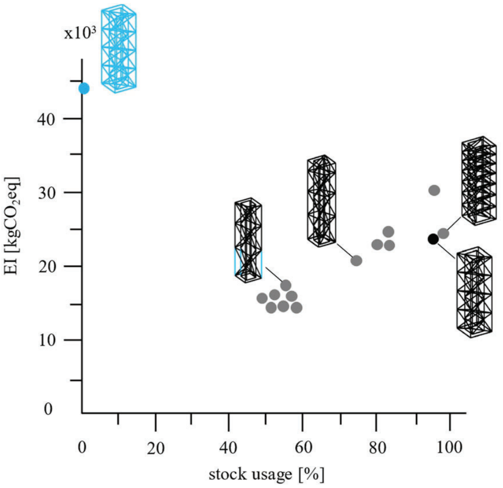

Figure 11. *Design iterations; black dot indicates final design, blue dot indicates final design made of entirely new elements*

After evaluating numerous designs through the optimization process described in Chapter 3, iteration 13 was determined to be the most suitable as the final design. This decision was made due to the high usage of old elements, corresponding to 91%. Furthermore, the design boasts a relatively low EI of 24,565 kgCO$_2$eq. Additionally, the design satisfied the aesthetic preferences of the designer. To validate this selection, in iteration 14, the EI of the final design was computed again, with the assumption that it was constructed solely using new elements. The results show an EI of 44,452 kgCO$_2$eq, indicating that the chosen design has a 45% lower EI compared to a comparable tower built entirely from new elements. The findings in Figure 11 also suggest a linear correlation between the EI and the stock elements used. This is likely due to the fact that only a few designs used

https://doi.org/10.52202/069179-0469

newly manufactured elements and were constructed almost exclusively with reused elements, resulting in a linear calculation of their EI through the corresponding LCA. Figure 12 presents renderings of the selected design to provide an understanding of how the new tower interacts with its environment. In addition to the outcome from iteration 13 shown in Table 2, a roof and cladding were added to protect the structural components from the weather.

Figure 12. *Renderings of the newly designed tower made of structural elements from the obsolete tower*

5 CONCLUSIONS

In conclusion, this study presents a novel framework for the design of timber structures from reused structural elements. The framework is validated through a case study of the Sauvabelin lookout tower in Lausanne, Switzerland. In this context, computational tools, such as Phoenix3D, can be employed to optimally utilize available stock elements. Results show that the introduced computational framework enables for the design of a new structures tailored to the available stock elements, i.e., making best use of available reused elements. Moreover, the proposed approach can significantly reduce the environmental impact of the new tower, with a reduction of 45% compared to a similar tower constructed entirely from new elements. The adoption of this framework has the potential to enhance sustainability in the construction sector and move towards a more circular economy.

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