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Designing with partially disassembled trusses: an automated approach

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Abstract

Structural component reuse has a significant potential environmental impact, as it reduces carbon emissions and construction waste and avoids sourcing raw materials. However, drawbacks of component reuse include more complex and longer deconstruction processes and a required change of approach to the structural design task. To simultaneously address these barriers, this paper presents an automated design framework for designing new planar truss structures from a library of partially disassembled truss components. Compared to stock-constrained design methods that reuse single elements, this work reduces the required deconstruction work by avoiding complete disassembly. Combining partially disassembled and new components is shown to be capable of generating diverse designs in a fast manner on a case study with a realistic stock library.

Keywords: Steel trusses, Steel reuse, Structural optimization, Genetic algorithm, Circular economy

1. Introduction

The construction industry consumes 50% of all global resources [1] and is responsible for almost 40% of global energy use and total greenhouse gas emissions [2]. For steel construction, the need to limit carbon emissions has translated to an increasing interest in achieving net-zero goals [3]. Reusing reclaimed components has been suggested as a potentially efficient carbon reduction strategy [4], renewing research interest in the topic in recent years [5–7]. However, the reuse of reclaimed components is hindered by simultaneously changing the requirements for the demolition (or deconstruction) process and the structural design approach. Conventional steel truss design, for example, relies on using single elements of (almost) any load capacity and length. Even if a reclaimed truss is fully dissembled to form a so-called stock library of single members, the structural design approach for a new design must account for the limited load capacities and finite lengths of the reclaimed library members. This work proposes to alleviate both the structural design and deconstruction demands associated with reclaimed steel truss design through a new automated design approach for planar trusses made from partially disassembled components.

2. Overview of the automated design method

Initially focusing on disassembly to triangular truss elements, the new design approach aggregates stock library components to form a new truss within a user-defined target area. The aggregation is fast and can, therefore, be coupled with a Genetic Algorithm (GA) to optimize the new designs in terms of required modifications to the used reclaimed components and the use of new material. The preliminary structural performances of optimized truss designs are subsequently verified through a Finite Element Analysis (FEA).

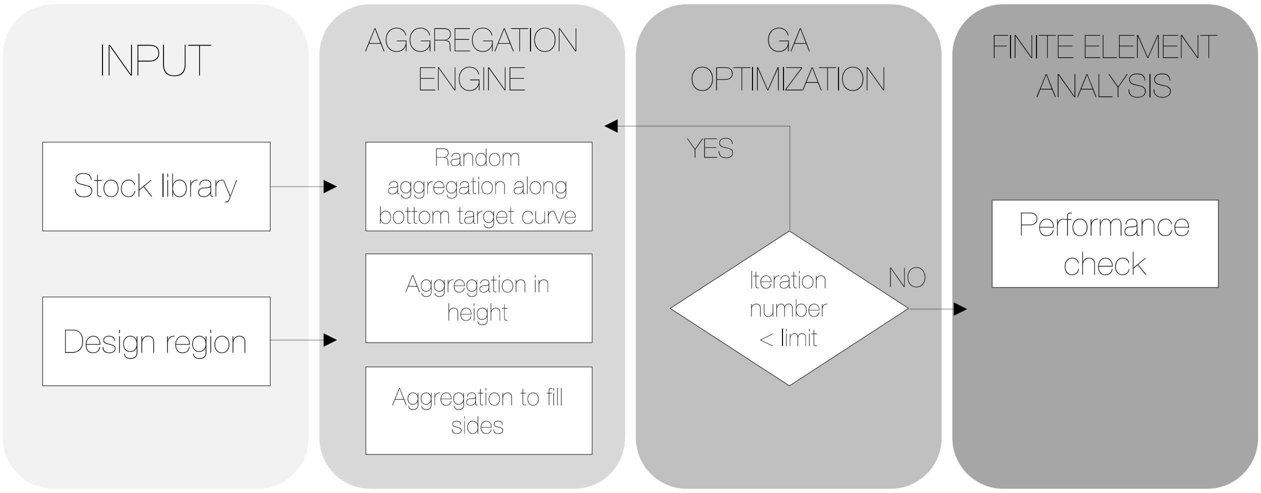


Figure 1: The proposed design framework for partially disassembled reclaimed trusses consisting of four modules.

Figure 1 gives an overview of the new automated design framework. The automated design approach consists of four modules: i) input, ii) aggregation engine, iii) optimization over trial designs, and iv) performance check of the optimized solution. The user initiates the design process by providing two types of input (Figure 2): the inventory of reclaimed steel trusses, which are herein partially disassembled into triangular components, and the design region that the new planar truss design should occupy with applied loads and boundary conditions. For details on the calibration of parameters, the reader is referred to [8].

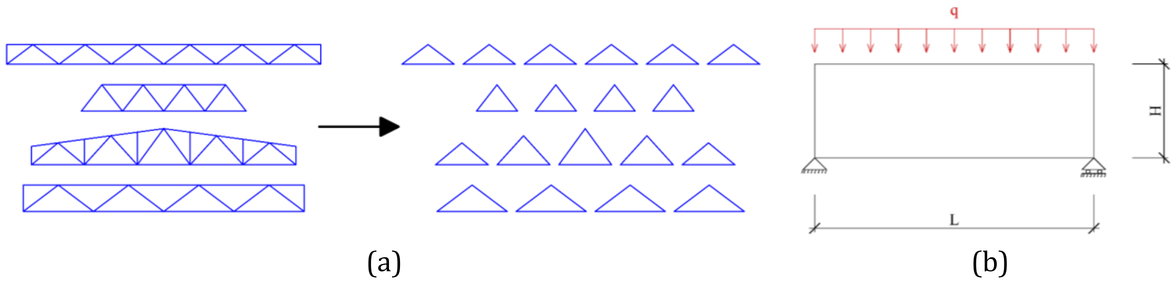


Figure 2: The framework requires two types of input: (a) reclaimed trusses that are partially disassembled into a stock library of triangular components, and (b) requirements for the new planar truss design that includes the target shape, applied loads, and boundary conditions. Adapted from [8].

Once the inputs are defined, the aggregation engine constructs a trial truss in three steps:

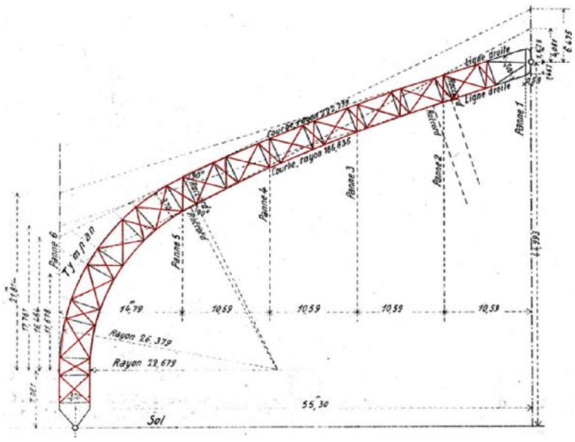
1. Initiated by a random operator, stock components are randomly aggregated horizontally along the bottom boundary of the target area. This may require cutting the last component to fit the target span.
2. The components are aggregated in height until the target height is reached; reclaimed components are cut to fit where needed. New elements are added where none of the reclaimed components fit or if excessive component cutting is required.
3. New components are added to fill the sides of the target area.

When the stock library allows for several distinct trial designs to be obtained, GA is used to optimize the design in terms of new material use and required reclaimed component cutting. The performance of the final design is checked with an FEA. The algorithm implementation, and the specific parameters and settings are detailed in [8].

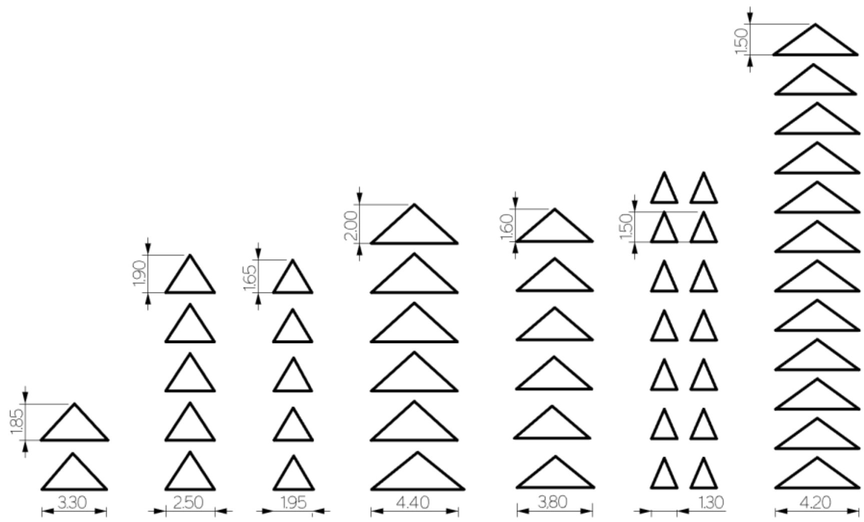
3. Case study results

The automated design approach with partially disassembled truss components is demonstrated using the original trusses from the Galérie des Machines. The Galérie des Machines was the largest wide-spanning iron-framed structure ever constructed when it was completed for the Universal Exposition of 1889 in Paris [9]. It consisted of twenty three-hinged truss arches spanning the 115-meter hall, as shown in Figure 3a. The structure was demolished in 1910. Figure 3b provides a construction drawing of a truss arch. The partially disassembled triangular components that would emerge from such an arch are indicated in red on the drawing. In this work, all lines are assumed straight. Seven different types of triangular components are identified and shown with their dimensions in Figure 3c.

(a)



(b)



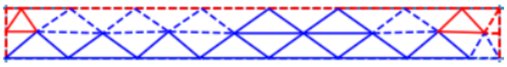
(c)

Figure 3: Case study stock library 3: Galérie des Machines [9]; (a) image of Galérie des Machines, and (b) construction drawing from (Atlas of Places). The resulting triangular component stock library used herein is shown in (c). Adapted from [8].

In this paper, a new rectangular, simply supported beam truss to support a roof structure, is designed based on the stock library from [8], shown in Figure 3c. The symmetry of the new designs is enforced by aggregating components in half the target shape and mirroring the obtained design. The library is, therefore, reduced and contains the partially disassembled components of half one truss arch from the Galérie des Machines with a total of 50 reclaimed triangular components.

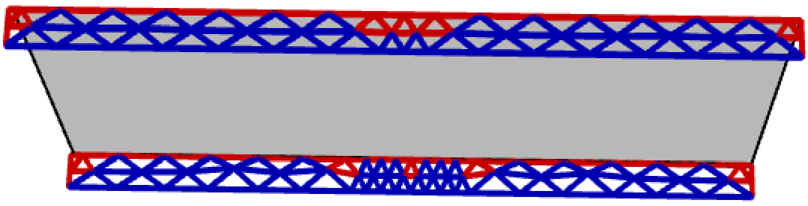
Two designs of different lengths are generated and shown in Figures 4 and 5, with half-span lengths (L/2) equal to 30 m and 20 m, respectively, each with a height of 3 m (and a 0.3 m height tolerance). The objective function for the optimization is the sum of L_{new} and L_{cut}. Here, L_{new} is the total length of new (red) components necessary, and L_{cut} is the total length of reclaimed component cut off; the dotted blue lines are the components that need to be cut.

Figures 4a and b show two different designs that are optimized for a span length of 60 meters within the algorithm's specific run of 1000 generated designs. Figure 4c shows a full 3D rendering of both trusses within the roof.



(a) L_{cut} = 2.27 m, L_{new} = 46.94 m

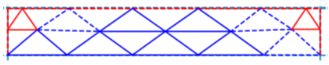
(b) L_{cut} = 2.06 m, L_{new} = 46.94 m



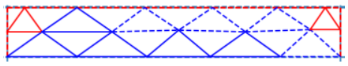
(c)

Figure 4: Case study 60-meter design and 3D rendering of the trusses supporting a roof structure

Figure 5a and b are two possible designs for a length of 40 meters. These designs are clearly more regular as fewer components are necessary to fill the target design shape. Figure 4c depicts a rendering where the red members are new material and the blue components are (fully or cut) reclaimed components from the Galérie des Machines.



(a) L_{cut} = 3.10 m, L_{new} = 32.88 m



(b) L_{cut} = 3.52 m, L_{new} = 33.22 m

(c)

Figure 5: Case study 40-meter design and 3D rendering

4. Conclusions

Greater reuse of reclaimed steel trusses has a significant potential to reduce the environmental impact of construction. However, it requires re-thinking both the demolition or deconstruction process as well as how the structural design task is approached. To simultaneously alleviate these concerns, this work proposes an automated approach that eases the design process while limiting the need for complete disassembly of reclaimed trusses.

The new framework requires the user to define a design region for the new design and aggregates partially disassembled triangular components while introducing new material members where necessary, to ensure that the new design matches the target shape. The new framework is demonstrated for new planar truss design using a case study library containing isosceles triangular components from a real structural example. The design is initiated by a random operator, allowing the generation of diverse designs if the stock library contains different component sizes. The framework generally generates a trial truss in 0.1 seconds and is, therefore, combined with GA optimization to identify high-performing layouts.

References

[1] European Commission, Sustainability Report on Buildings and Construction, (n.d.). https://single-market-economy.ec.europa.eu/industry/sustainability/buildings-and-construction_en (accessed September 4, 2023).

[2] UN Environment Program, 2022 Global Status Report for Buildings and Construction, (n.d.). https://www.unep.org/resources/publication/2022-global-status-report-buildings-and-construction#:~:text=CO2%20emissions%20from%20buildings%20operations,to%20achieve%20decarbonization%20by%202050 (accessed September 4, 2023).

[3] International Energy Agency, Iron and Steel Technology Roadmap, 2020. https://www.iea.org/reports/iron-and-steel-technology-roadmap (accessed September 26, 2023).

[4] J.M. Allwood, J.M. Cullen, M.A. Carruth, D.R. Cooper, M. Mc Brien, R.L. Milford, M.C. Moynihan, A.C.H. Patel, Sustainable materials: with both eyes open, UIT Cambridge Limited, Cambridge, UK, 2012.

[5] C. De Wolf, E. Hoxha, C. Fivet, Comparison of environmental assessment methods when reusing building components: A case study, Sustain Cities Soc 61 (2020) 102322. https://doi.org/10.1016/J.SCS.2020.102322.

[6] J. Brütting, G. Senatore, C. Fivet, Form follows availability - Designing structures through reuse, in: Journal of the International Association for Shell and Spatial Structures, 2019: pp. 257–265.

[7] J. Brütting, C. Vandervaeren, G. Senatore, N. De Temmerman, C. Fivet, Environmental impact minimization of reticular structures made of reused and new elements through Life Cycle Assessment and Mixed-Integer Linear Programming, Energy Build 215 (2020) 109827. https://doi.org/10.1016/J.ENBUILD.2020.109827.

[8] A. Van Marcke, V. Laghi, J.V. Carstensen, Automated planar truss design with reclaimed partially disassembled steel truss components, Journal of Building Engineering 84 (2024). https://doi.org/10.1016/j.jobe.2024.108458.

[9] J.W. Stamper, The Galerie des Machines of the 1889 Paris World's Fair, Technol Cult 30 (1989) 330. https://doi.org/10.2307/3105107.

[10] Atlas of Places, (n.d.). https://www.atlasofplaces.com (accessed September 26, 2023).