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Optimum Truss Design with Reused Stock Elements

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Abstract

This paper proposes the application of optimization techniques to design reticular structures made from a stock of reused elements. Still little explored, the reuse of structural components over multiple service lives has the potential to reduce the environmental impact of building structures. Construction based on *reuse* avoids sourcing new material, reduces superfluous waste, and requires little energy. However, designing a structure from a stock of reclaimed elements entails a change of paradigm. In contrast to conventional design practice, the structure geometry and topology depends on element stock characteristics, e.g. available cross sections and lengths. This paper extends discrete structural optimization formulations to assign stock elements to truss systems. An iterative approach is proposed: 1) element assignment and topology optimization are first carried out; 2) geometry optimization follows thereafter to improve the system geometry to reduce cut-off waste for assigned stock elements. Two case studies are presented to validate the proposed design method and to quantify environmental impact reductions of structures made from reused elements.

Keywords: structural optimization, trusses, reuse, stock elements, embodied energy

1. Introduction

The building sector is a major contributor to material consumption [1], energy use, greenhouse gas emission [2], and waste production [3]. Most of the *embodied impacts* of buildings [4], e.g. related to material extraction, production, construction and demolition, are due to the load bearing systems [5]. One way to reduce building embodied impacts is *circular economy* [6]. Circular economy advocates closed loops within the service life of materials and components. Unlike *recycling*, *reuse* requires minimum energy for reprocessing [7]. However, from the standpoint of a structural engineer, reuse involves reversing the conventional structural design process. The structural layout (geometry and topology) depends on a-priori given mechanical and geometric properties of available stock elements [8]. Recent examples of such design philosophy based on reuse are the London Olympic stadium whose roof is made of 20 % steel tubes reclaimed from a nearby infrastructure project [2] and the BedZED project, a residential and office building, whose structure is made of 90 % reclaimed elements [7].

2. Structural optimization with stock constraints

2.1 Related work

Generally, the goal of structural optimization is to find optimal structural layouts for a given set of loads and boundary conditions. Reticular structures are often optimized by adjusting their topology and cross section sizes starting from a *ground structure*, which is the set of all possible member sites. Geometry optimization might be carried out to change the node positions to obtain optimal shapes under applied loads. To reduce optimization complexity, often cross section areas are treated as continuous variables. In practice, because only a limited set of standard cross sections is available, discrete structural optimization should be employed. For this case, Rasmussen and Stolpe [9] formulated topology and discrete sizing optimization as a mixed-binary problem that can be solved to global optimality employing combinatorial optimization techniques such as branch-and-bound methods.

Usually, in structural optimization it is assumed that all the elements of an optimized system can be produced with required cross sections and lengths. Conversely, when reusing structural elements from a stock, the number of available cross section types is restricted and the structure geometry has to comply with available element lengths. Structural optimization with stock constraints has so far received little attention. Fujitani and Fuji [10] employed evolutionary algorithms to optimize plane frames from a stock of cross-sections, but without accounting for available element lengths. Bukauskas et al. [11] presented strategies to form-fit a stock of wood logs to statically determinate trusses employing algorithms that have been developed for bin-packing problems.

2.2 Optimization formulation

An extension of discrete optimization formulations [9] for truss structures to include stock constraints has been previously presented by Brütting et al. [12]. This method is summarized in following sections and a new extension is presented in section 2.2.3.

2.2.1 Assignment Problem

The selection of suitable elements from a stock and their optimal positioning in a structure can be formulated as an assignment problem of combinatorial nature. The same process is also employed to vary the topology of the structure when no element is assigned. Figure 1 (a) shows an optimized cantilever truss under the load F obtained from the ground structure (indicated by dashed lines) and using the stock illustrated in Figure 1 (c). The stock comprises six groups and is characterized by type of material, cross section areas ***a***, lengths ***l*** and number of available elements ***n***. The assignment of an element from stock group j at position i in the structure, is represented by an entry $t_{i,j} = 1$ in the assignment matrix ***T***, shown in Figure 1 (b). Only one assignment per position is allowed. The number of selected bars per group is bounded by the corresponding availability.

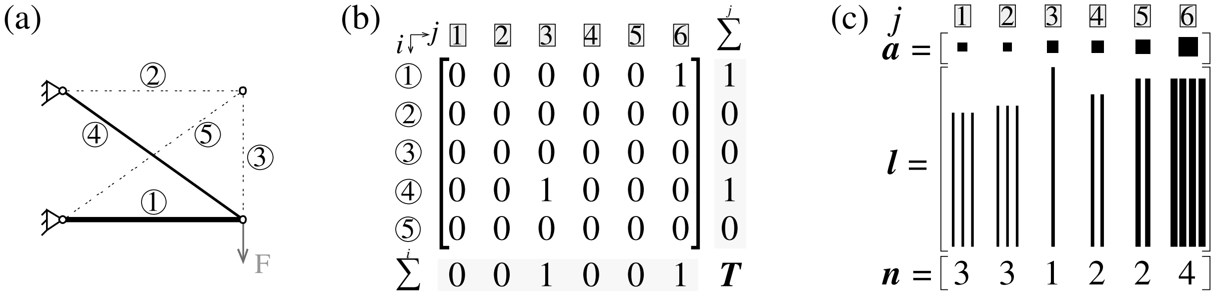

Figure 1. Assignment of available stock elements: (a) ground structure, (b) assignment matrix, (c) stock.

2.2.2 Layout optimization

In combination with assignment optimization, a general structural layout optimization method has been formulated to account for the reuse of structural elements. The reader is referred to [12] for a detailed explanation of the method. The formulation accounts for stress, Euler buckling and deflection constraints under multiple load cases including self-weight. A sequential approach (see Figure 2) to separate assignment and geometry optimization is suggested.

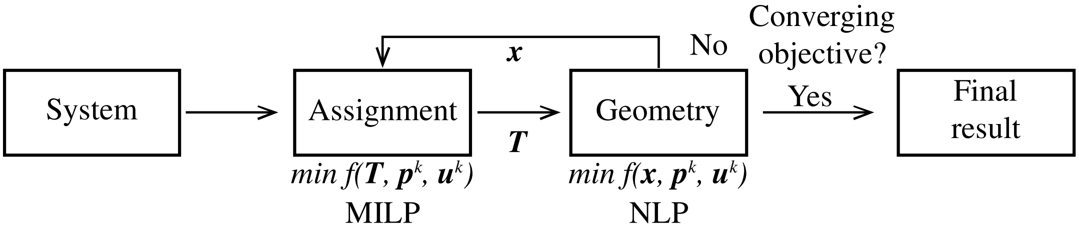

Figure 2. Iterative optimization process, adapted from [12].

Element assignment and topology optimization (geometry is fixed) are carried out by decoupling structural equilibrium and elastic compatibility and computing assignment variables $t_{i,j}$ and state variables (member forces and nodal displacements) simultaneously [9] in the optimization. This allows to efficiently solve the assignment problem to global optimality using Mixed-Integer Linear Programming (MILP) [9]. In the second step, for a fixed assignment and topology, geometry optimization is carried out by varying the nodal position vector $\boldsymbol{x}$. The objective of assignment optimization is to reduce structural mass and consequently to maximize element capacity utilization. Geometry optimization is then carried out to reduce cut-off waste by matching nodal positions to assigned element lengths.

2.2.3 Element buffer

Starting from the ground structure (step 1), it might not be possible to assign all the required stock elements because they might be too short for certain positions. However, because of the iterative geometry optimization, successive nodal changes might allow their assignment in later steps. As an extension to the method given in [12], this paper introduces a *buffer* on the element lengths to allow infeasible length assignments at the start of the iterative search. This buffer reduces to zero after a fixed number of iterations. In other words, the search space is temporarily increased to allow more assignment combinations but constraints on the element lengths are satisfied for the final outcome.

2.3 Embodied Energy and Carbon

Life Cycle Assessment (LCA) is employed to quantify the embodied energy and carbon of structures obtained using the method described in 2.2. This assessment accounts the impacts related to the supply of stock elements through selective deconstruction and their transport to the building site [12]. The embodied energy of structures made from reused elements is a function of the structural mass *M* as well as the cut-off waste Δ*M*:

$$E_{Reuse} = 3.25\frac{MJ}{kg}M + 3.24\frac{MJ}{kg}\Delta M \tag{1}$$

3. Case studies

3.1 Cantilever truss

3.1.1 System and Stock

Figure 3 (a) shows a 10-bar cantilever ground structure with a span *S* = 4.00 m and height 2.00 m. A load F = 10 kN is applied at the bottom end. The free nodes are allowed to vary between ± 80 cm from their initial position (blue domains). The domain of the loaded node is constrained to maintain a minimum horizontal span of 4.00 m. Two stock configurations consisting of steel bars with standard circular hollow sections (CHS) are illustrated in Figure 3 (b) and (c).

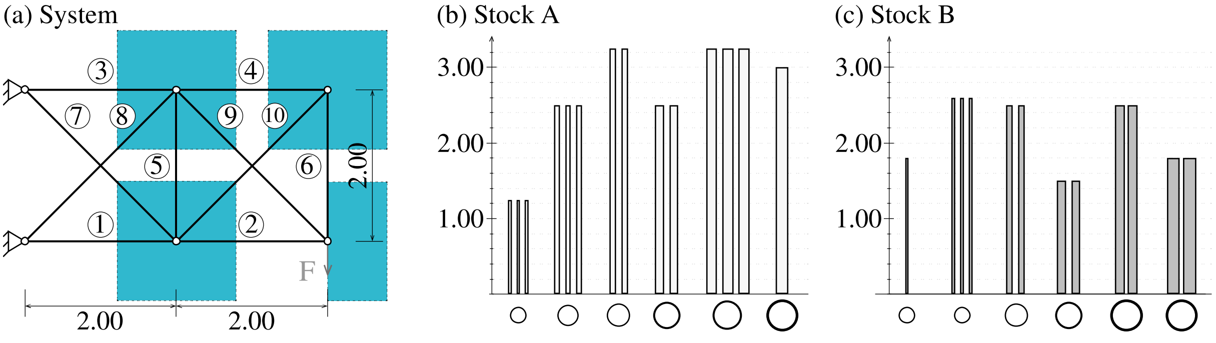

Figure 3. (a) 10-bar cantilever ground structure, (b) stock A, (c) stock B.

It is assumed that the steel bars have a yield strength of 235 MPa, a Young's modulus of 210 GPa and a density of 7850 kg/m^3. Table 1 summarizes cross-section types and element lengths for stocks A and B. The number of available elements per stock group is indicated in Figure 3 (c) and (d) respectively.

Table 1. Characterization - Stock A and B

Stock A	CHS		21.3x3.2	33.7x3.2	33.7x4.0	42.4x4.0	42.4x5.0	48.3x5.0
	a_j	[cm^2]	1.82	3.07	3.73	4.83	5.87	6.80
	l_j	[m]	1.25	2.50	3.25	2.50	3.25	3.00
Stock B	CHS		21.3x3.2	21.3x3.2	33.7x4.0	42.4x4.0	48.3x5.0	48.3x5.0
	a_j	[cm^2]	1.82	1.82	3.73	4.83	6.80	6.80
	l_j	[m]	1.80	2.60	2.50	1.50	2.50	1.80

3.1.2 Optimization results

Four cases are considered: (a) pure assignment and topology optimization from stock A; (b) layout optimization without element buffer from stock A; (c) and (d) layout optimization with element buffer from stock A and B respectively.

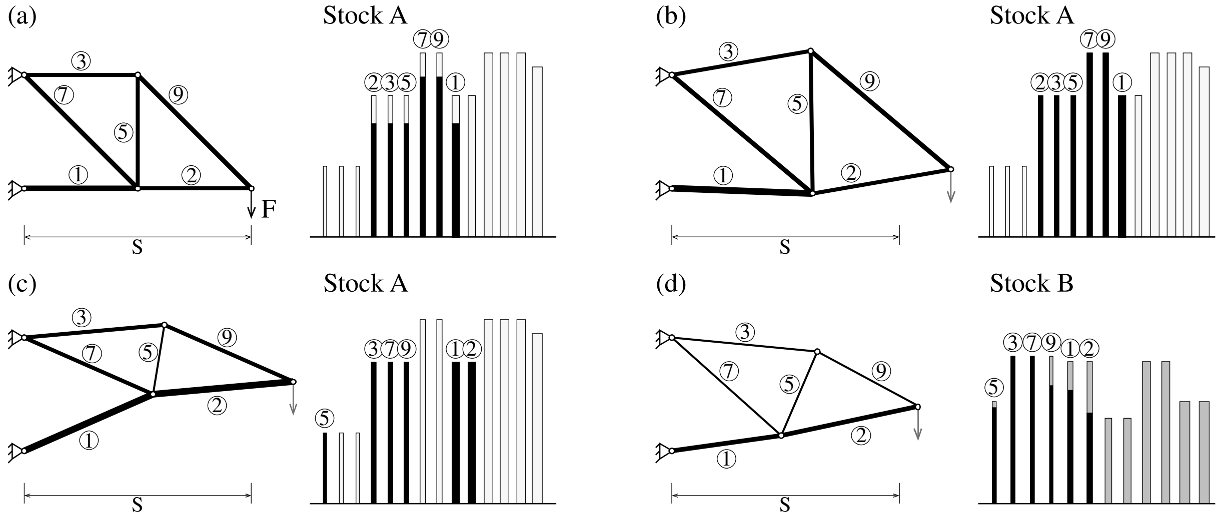

Figure 4. Cantilever truss results: (a) pure assignment and topology optimization, (b) layout optimization without element buffer, (c) and (d) layout optimization with element buffer. In the stock illustrations, black bars represents system members and grey bars unused stock elements or cut-off.

Table 2 summarizes optimization metrics for all cases ((e) and (f) are discussed in next section). Case (a) results in the biggest cut-off waste ΔM, whereas cases (b) and (c) achieve zero waste because of geometry optimization. Case (d) achieves the lowest mass amongst all the reuse systems because stock B has a larger availability of small sections than stock A. In cases (a) and (b) the small cross sections cannot be used because of their short length. In case (c), the assignment of a small cross section at position ⑤ is possible via the element buffer technique described in section 2.2.3. The element buffer also allowed obtaining an optimal solution in case (d) where all the stock elements are shorter than the initial ground structure diagonals.

Table 2. Cantilever results.

		(a)	(b)	(c)	(d)	(e)	(f)
M	[kg]	38.6	46.6	38.8	25.7	17.7	13.3
ΔM	[kg]	8.00	0	0	2.6	0	0
Mean element utilization	[%]	33 %	51 %	53 %	66 %	75 %	100 %

3.1.3 Embodied impact savings

The embodied energy and carbon of the systems made of reused elements are compared to those of weight-optimized structures made from newly produced elements. The environmental impacts for the reuse cases are computed as described in section 2.3. The weight-optimized cases with new elements are obtained via: (e) a sequential geometry and discrete cross section optimization allowing all standard CSH sections reported in EN 10220 [13], and (f) a simultaneous cross section and geometry optimization in which cross section radii are the design variables and the wall thickness is set to 10 % of the radius. With regard to new elements, their embodied energy intensity of 13.22 MJ/kg includes the production from conventional steel (with recycled content) and transport impacts [12]. The bar chart in Figure 5 shows that reusing structural elements results in a significant reduction of embodied carbon and energy, even though the systems with newly produced elements have a smaller mass and higher mean capacity utilization (see Table 2). Member capacity utilization indicates that reusing structural elements can result in oversized structures when there is a limited availability of small cross sections.

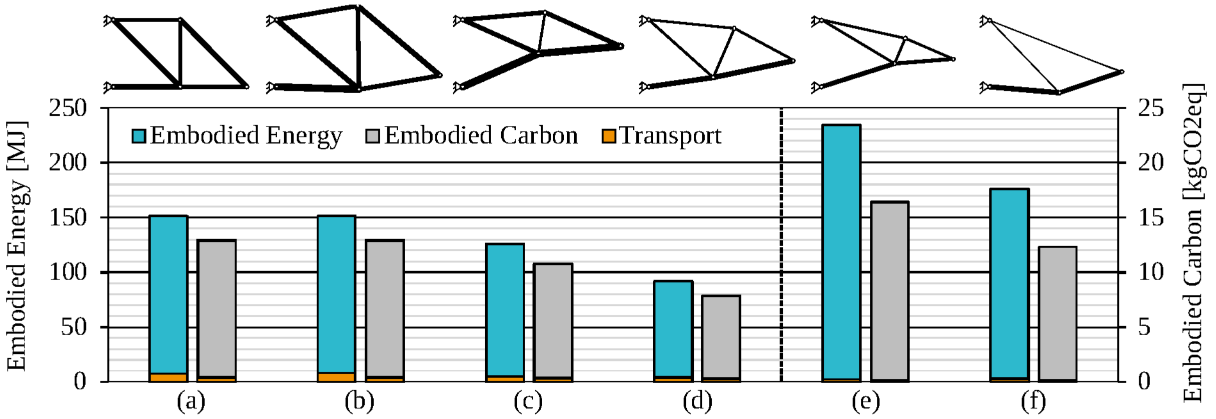

Figure 5. Comparison between structures: (a) to (d) made from reused elements, (e) and (f) of new steel.

3.2 A train station roof built from power transmission pylons

This case study offers an opportunity to propose a structural scheme for the main train station roof in Lausanne (Vaud, Switzerland) using elements reclaimed from power transmission pylons. The redesign of Lausanne's train station is currently under planning to respond to an increase in passenger demand. The pylons, shown in Figure 6 (a), were built in the 1950s in the region of Wallis, Switzerland. Six power transmission lines consisting of such pylons will be replaced by one high voltage line. However, the pylon members have not yet reached the service life for which they had been designed.

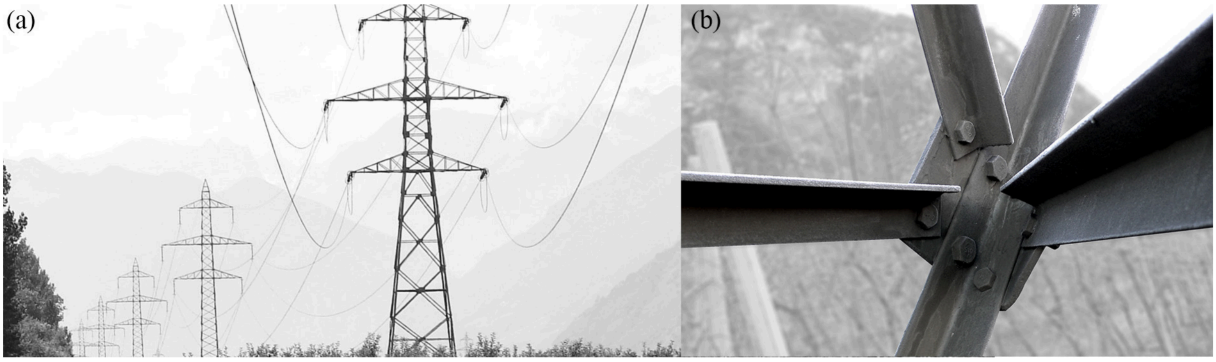

Figure 6. (a) Power transmission line (Swissgrid, 2017), (b) typical sections and connection detail.

3.2.1 Stock characterization

The pylons consist of L-section steel bars connected by plates and bolts as shown in Figure 6 (b). The power line operator *Swissgrid* intends to disassemble the members piece by piece. The composition of the element stock has been obtained from archive plans, one of which is shown in Figure 7 (a). One single line comprises about 50 pylons, totaling up to 19'000 bars. Figure 7 (b) shows a scatter diagram of the 322 different bar groups, which have been characterized by length, cross-section, connection detailing and availability. Similar groups are merged to reduce computational complexity. The stock element capacities in tension and compression account for the existing hole patterns as well as the flexural-torsional buckling behavior of the L-profiles.

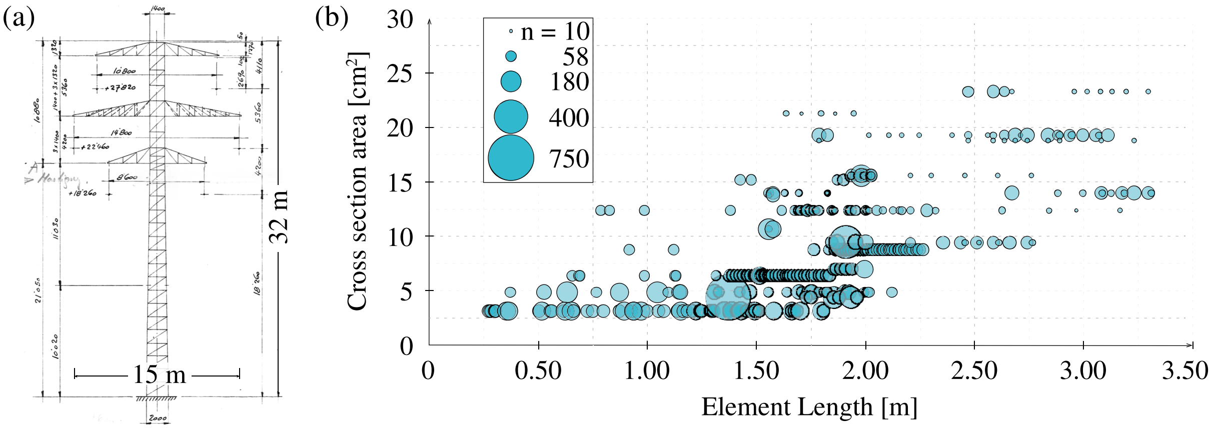

Figure 7. (a) Original drawing of one pylon section (Swissgrid, 2017), (b) stock composition; dot areas are proportional to the number of available elements per section and length.

3.2.2 *Roof structure design*

Figure 8 presents a schematic view of the intended structural design. The structure, comprising three central units and two side units, spans over four double-tracks to form an array of three-hinged frame trusses. Parallel to the tracks, secondary trusses span 10 m between multiple transverse sections. The secondary trusses are taken from the electric pylons as complete modules. A roof cladding is fixed with custom connections compensating for the uneven node positions of the truss top chords.

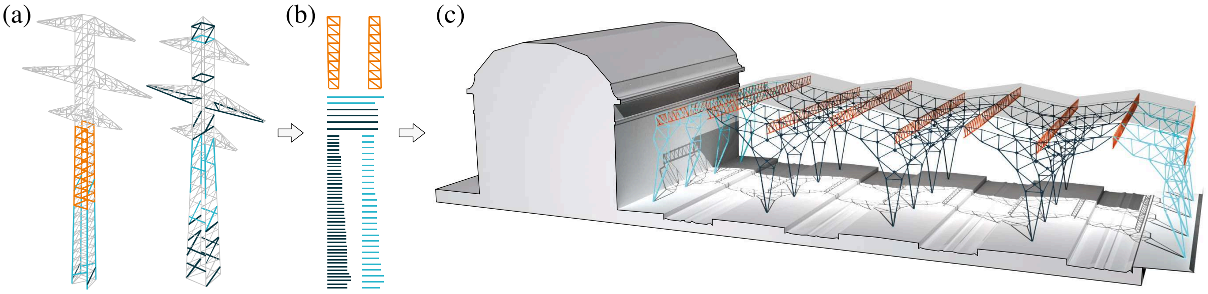

Figure 8. (a) Suspension and anchor pylon, (b) reused members, (c) final structural system.

Figure 9 (a) shows the ground structure of side and central units. The ground structure layout is predetermined to meet site constraints, such as support locations and required heights as well as to fit stock characteristics such as the element lengths.

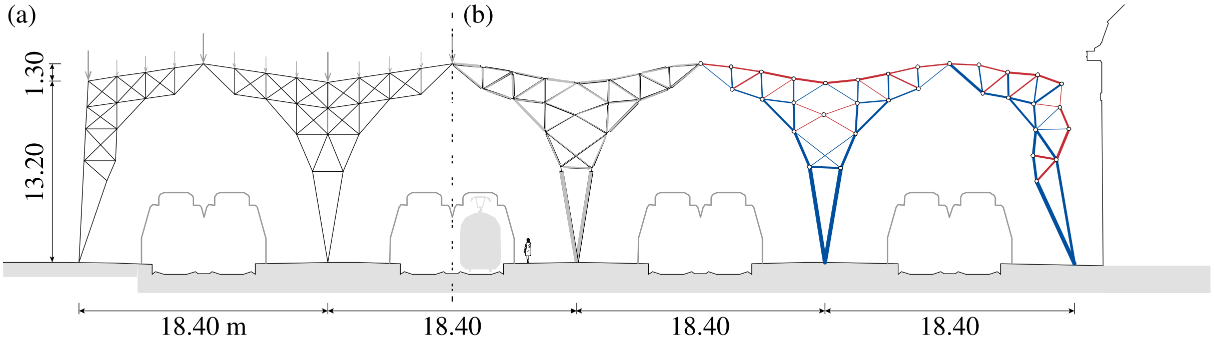

Figure 9. Transversal roof section: (a) initial ground structure, (b) final layout and force distribution

The optimization method outlined in section 2.2 is adapted to consider stock specific constraints: geometry optimization is employed to adjust the nodal distances to be greater than the assigned element lengths. This allows combining elements at nodes with custom connection plates reusing existing holes at element ends. Load cases include combinations of self-weight, dead load, snow and wind. Ultimate limit (ULS) and serviceability limit state (SLS) are set as optimization constraints.

Figure 10 shows (a) the initial and (b) the final layout for the end units of the roof. Figure 10 (c) maps the internal forces onto the structure geometry where the line thickness is proportional to the force magnitude. Figure 10 (d, left) shows the capacity utilization of each assigned stock element considering tension, compression and buckling. Figure 10 (d, right) illustrates assignment and use of stock. For most bar positions, the distance between the corresponding nodes is bigger than the assigned stock element length. In these cases, custom connections plates are employed to join the bars, reusing also the existing hole patterns at the element ends. Similar considerations apply to the central unit shown in Figure 9 (b), which are not reported here for brevity. Dissimilar optimal geometries for side and central units are due to the influence of stock element lengths and the asymmetry of the side unit ground structure. The full structural system (200 × 75 m, 20 bays) was post analyzed for more load combinations than used in the optimization. Only minor changes in topology and local reinforcement were required to guarantee the functioning of the whole roof structure.

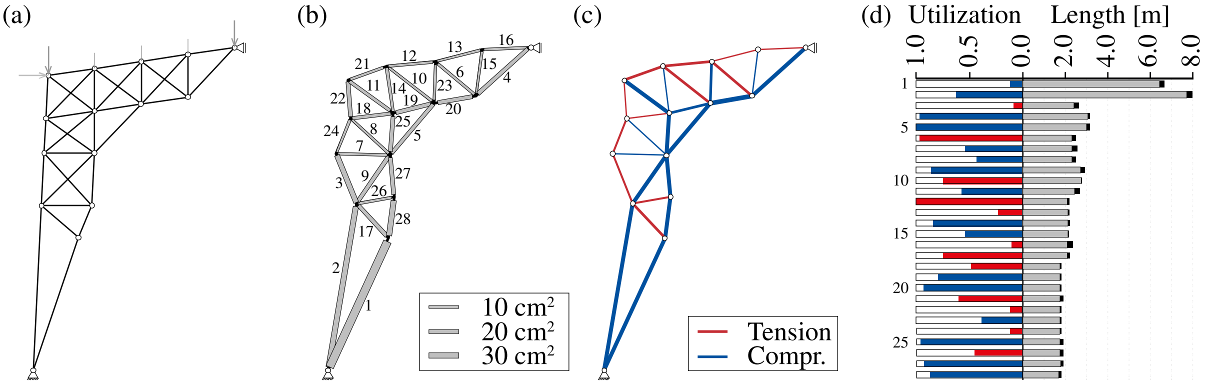

Figure 10. Side unit: (a) ground structure, (b) final layout, (c) internal force distribution (d) stock use; grey: length of stock elements; black: excess length between two nodes.

3.2.3 *Environmental impact comparison*

The environmental impacts of the structure made from reused elements are compared to those of a structure with identical layout (topology and geometry) optimized for minimum weight. For this case the cross section areas are discrete variables but all L-section shapes reported in EN 10056-1 [14] are available in unlimited quantity. Table 3 indicates obtained optimization results for one transversal section with three central units and two side units. The structure made from reused elements (b) has 50 % more mass with respect to the weight-optimized solution (a) which is made of elements of smaller cross sections, resulting in a better capacity utilization. However, the embodied energy and GHG emissions of the structure made of reused elements are 63 % and 56 % lower respectively than those of the weight-optimized solution.

Table 3. Environmental impacts of (a) the benchmark case (b) the reuse case.

Metric	Unit	(a) New elements	(b) Reused elements	(b) vs. (a)
Mass	[kg]	4’400	6’600	+50 %
Mean cross section area	[cm^2]	9.8	12.00	+ 22 %
Mean element utilization	[%]	84 %	62 %	- 22 % (abs)
Embodied energy	[MJ]	58’500	21’400	- 63 %
GHG emissions	[kgCO2eq]	4’100	1’800	- 56 %

4. Conclusion

This paper presented applications of structural optimization methods whereby structural layouts are obtained from a given stock of reclaimed elements. Case studies have shown that element assignment and geometry optimization can be applied to obtain optimal structures satisfying design criteria (ULS and SLS) that commensurate with realistic scenarios. Even though structures made from reused elements have a higher mass and a lower element capacity utilization, they embody significantly less energy and carbon with respect to structures made from new elements.

Future work will investigate the generality of this conclusion through other case studies. The two-step method comprising element assignment followed by geometry optimization presented in this paper might result in local optima. Future work will look into methods to search more efficiently the solution space including simultaneous optimization of element assignment, topology and geometry.

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