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Reuse in Architecture and Structural Design

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Introduction

The construction industry has an extensive impact on the global environment (Fig. 1) and will be facing three big challenges in the next decades: reducing its resource consumption, decreasing its energy use, and limiting its waste production. This is even more crucial, considering global population growth and increasing urbanization. Consequently, a shift of paradigm from a linear economy of make use dispose, towards a circular economy that advocates closed loops within the service life of materials and components is required (Fig. 2). Recycling currently is the common strategy to make use of obsolete materials; however, it involves energy for reprocessing (e.g. melting steel scrap). Instead, direct reuse of components close to their original form has the potential to reduce environmental impacts further because sourcing additional raw material is avoided and only few energy is spent for transformation [1]. In the case of buildings and infrastructures, load-bearing systems contribute the most to the embodied environmental impacts. This is because of their big mass and energy intensive construction process. These observations suggest that reusing structural elements has large potential to reduce the environmental footprint of building structures. Reused components may consequently have a longer service life than the systems to which they initially belonged and disassembled buildings become a mine for new constructions.

This idea is of course not a today's invention, but has found application already far in the past as well as in recent building projects. Before the industrialization era, most building materials were sourced locally and reuse of building materials and components was the rule because it was more cost and time efficient than new production [1]. The scarcity of building materials had to be considered in design and construction.

A classic example is the reuse of bricks (spolia) throughout the Roman and Greek eras or in post-war times. Remarkable are also the stone columns of the Great Mosque of Cordoba, Spain, which were reused from nearby Roman and Visigoth ruins to support Moorish double arches (Fig. 4 (a)). At this time it was more cost and labor efficient to reuse stone pillars instead of manually hewing new ones in quarries. In the early 20th century in Switzerland many bridges were built using formwork made from reused timber logs (Fig. 4 (f)). Wood was a scarce material at that time. The „Big Dig House" in Lexington, MA, USA reuses steel girders from a dismantled Boston highway (Fig. 4 (b) and (d)). The steel elements were cleaned, repainted and adapted to fit their new setting. Another outstanding structure is the London Olympic Stadium (Fig. 4 (e)), whose roof truss incorporates 2500 tons of steel pipeline tubes reused from a nearby development project. This means that 25% of the roof structure is made from material which was formerly devoted as scrap.

A grid shell pavilion made from 210 reused skis has been developed by researches at EPFL's Structural Xploration Lab (Fig. 8). The skis are arranged in a square grid which is initially flat and then actively bent into a double curved shape (Fig. 8 (d)). The skis were locally sourced from junkyards and are normally considered special waste due to their composite buildup. Every ski has been tested for its bending stiffness (Fig. 8 (b)) and strength to optimally use the inherent mechanical properties, i.e. more flexible skis were placed at high curvature zones. The special combination of multiple skis to foldable units (Fig. 8 (c)) allowed to assemble and reassemble the structure in different places in Switzerland, France and Belgium.

Research

While historic and contemporary projects, especially in Europe, highlight the environmental, time or cost benefits of building with reclaimed (structural) elements, many technological challenges remain. Buildings have to be carefully disassembled, which is often only possible for steel or wooden structures that are joined with reversible connections, or when elements can be cut and member ends are reshaped to fit new settings. Further, the quality and structural capacity of reclaimed elements has to be ensured. Under these assumptions, this research focuses on the standpoint of composing building structures from a stock of reclaimed elements. This entails reversing the conventional design process. The constrained availability of elements dictates the layout (topology and geometry) of the designed structure due to the a-priori given geometric and mechanical properties (Fig. 3). The design shifts towards a "form follows availability" paradigm [1].

Structural optimization methods, which traditionally seek best performing structural systems under given boundary conditions, can be extended to integrate and facilitate element reuse in structural design. This research uses the combination of combinatorial optimization and form-finding methods to design reticulated structures from a given stock of reclaimed elements [2], where: 1) available elements are grouped by material, structural capacity and dimensions, 2) an optimal assignment of a subset of stock elements into a structural system is performed, and 3) the structure geometry is optimized. Generally, the assignment step 2) minimizes the structural weight to optimally utilize the available element capacities, whereas the geometry optimization step 3) is carried out to match truss geometry and available element lengths.

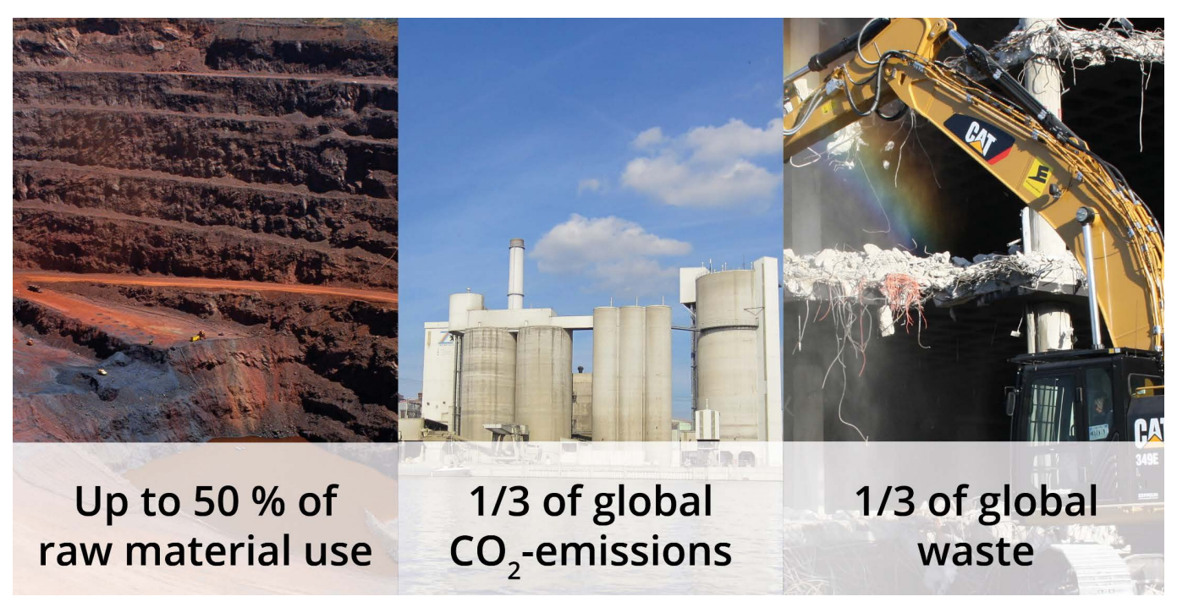

Fig. 1: Responsibility of the building sector

Results

The optimization method is applied to form-find truss systems subject to differently composed stocks. In each case, varying cross section sizes or element lengths result in a different outcome of the designs. Fig. 5 (a) shows a typical roof truss design, which is loaded at the top chord and is used as the initial topology for the introduced optimization method. The obtained layout for the case of using Stock A is reported in Fig. 5 (b). This stock consist of elements with 3.00 m length which are n = 4 times available for each of the six cross-section groups. Due to limitations of the stock to 3.00 m elements only, the truss layout contains two arrays of three almost equilateral triangles. For the truss made from Stock B, which is composed of equivalent cross section groups but with variable element lengths, the found geometry is shallower and vaulted.

Another result is a case study design of a structural scheme for the main train station roof in Lausanne (Vaud, Switzerland) using elements reclaimed from power transmission pylons (Fig. 6). The redesign of Lausanne's train station is currently under planning to respond to an increase in passenger demand. The pylons, shown in Fig. 6 (a), were built in the 1950s in the region of Wallis, Switzerland. The pylons consist of L-section steel bars connected by plates and bolts. The composition of the element stock has been obtained from archive plans, one of which is shown in Fig. 6 (b). Fig. 6 (c) 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. The optimization method outlined above is used to form find the layout of the trusses containing the reused pylon members.

When comparing the embodied (grey) energy of truss structures made from reused elements against those of weight-optimized ones made with conventional recycled steel (Fig. 7 (a)), it is visible that the reuse structures might be heavier due to limitations on the availability of small sections in the stock. Yet because energy is saved through reuse instead of remelting scrap steel, the truss structures from reused elements embody significantly less energy and cause less greenhouse gas emissions (Fig. 7 (b)) [2].

Conclusion

The proposed optimization and form finding method renders a first step towards facilitating the design with reused elements where the outcome is not as predictable as in the well-established conventional structural design process. Future research will extend this method towards different structural typologies such as bending and frame systems. Further, the question of customized connection details enabling the joining of stock elements has to be addressed.

References

[1] Gorgolewski, Mark: Resource Salvation – The Architecture of Reuse. Wiley, Hoboken 2017.

[2] Brütting, Jan, Senatore, Gennaro, and Fivet, Corentin: Optimization Formulations for the Design of Low Embodied Energy Structures Made from Reused Elements. Springer, 2018

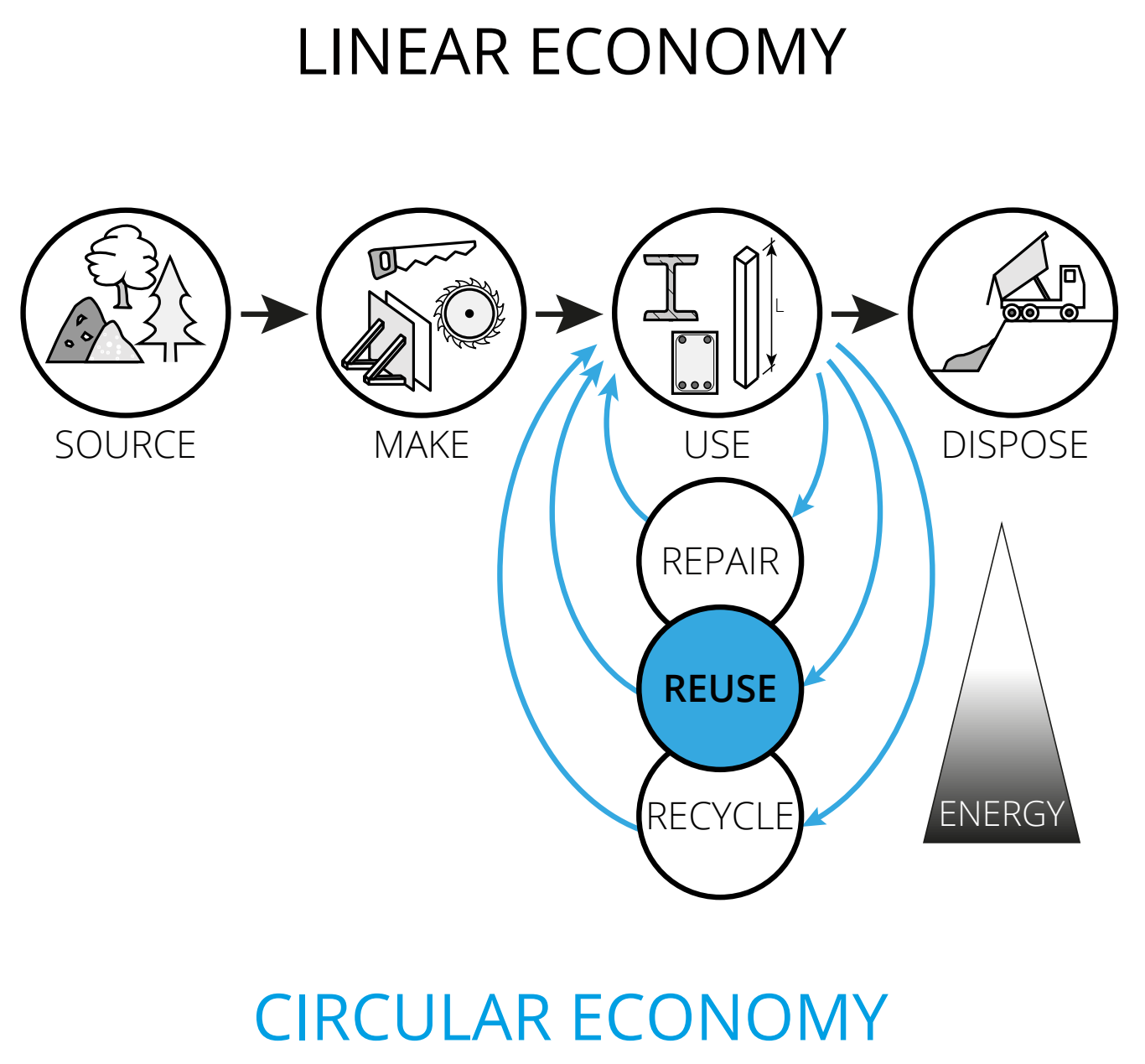

Fig. 2: Linear and Circular Economy.

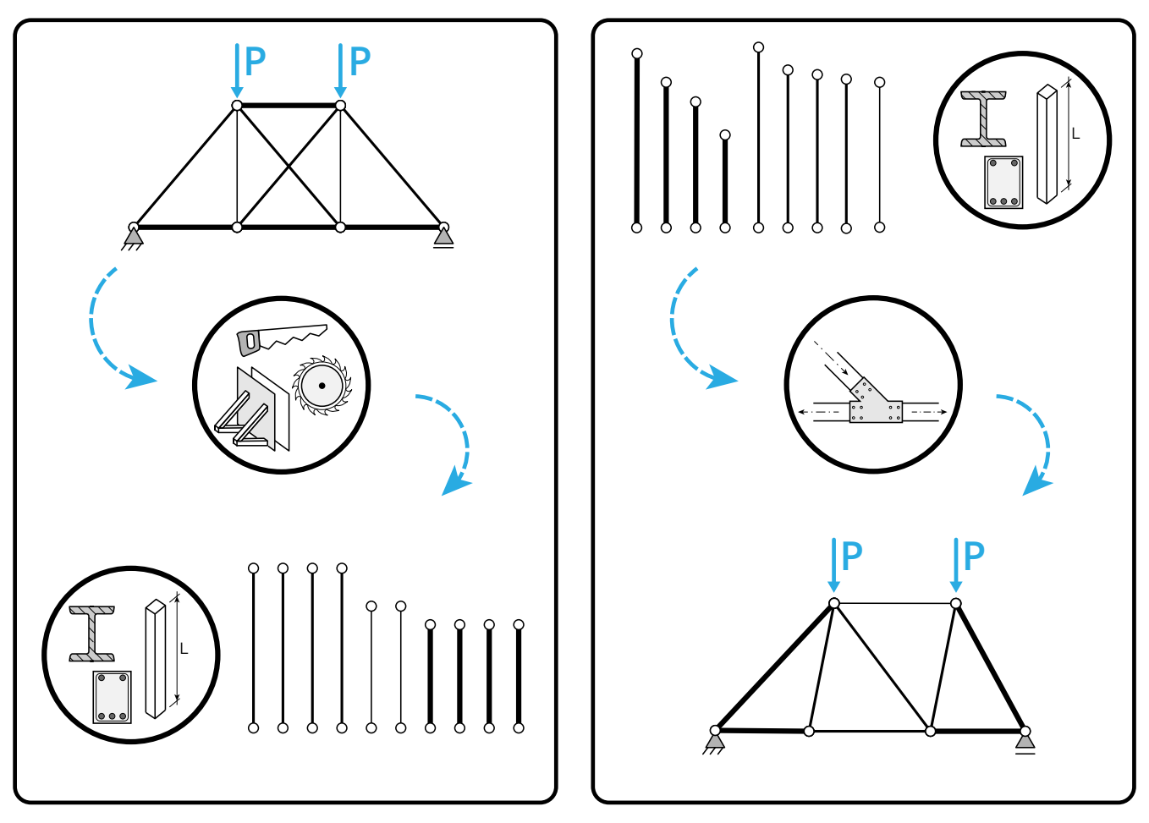

Fig. 3: Conventional and Reverse Design Process

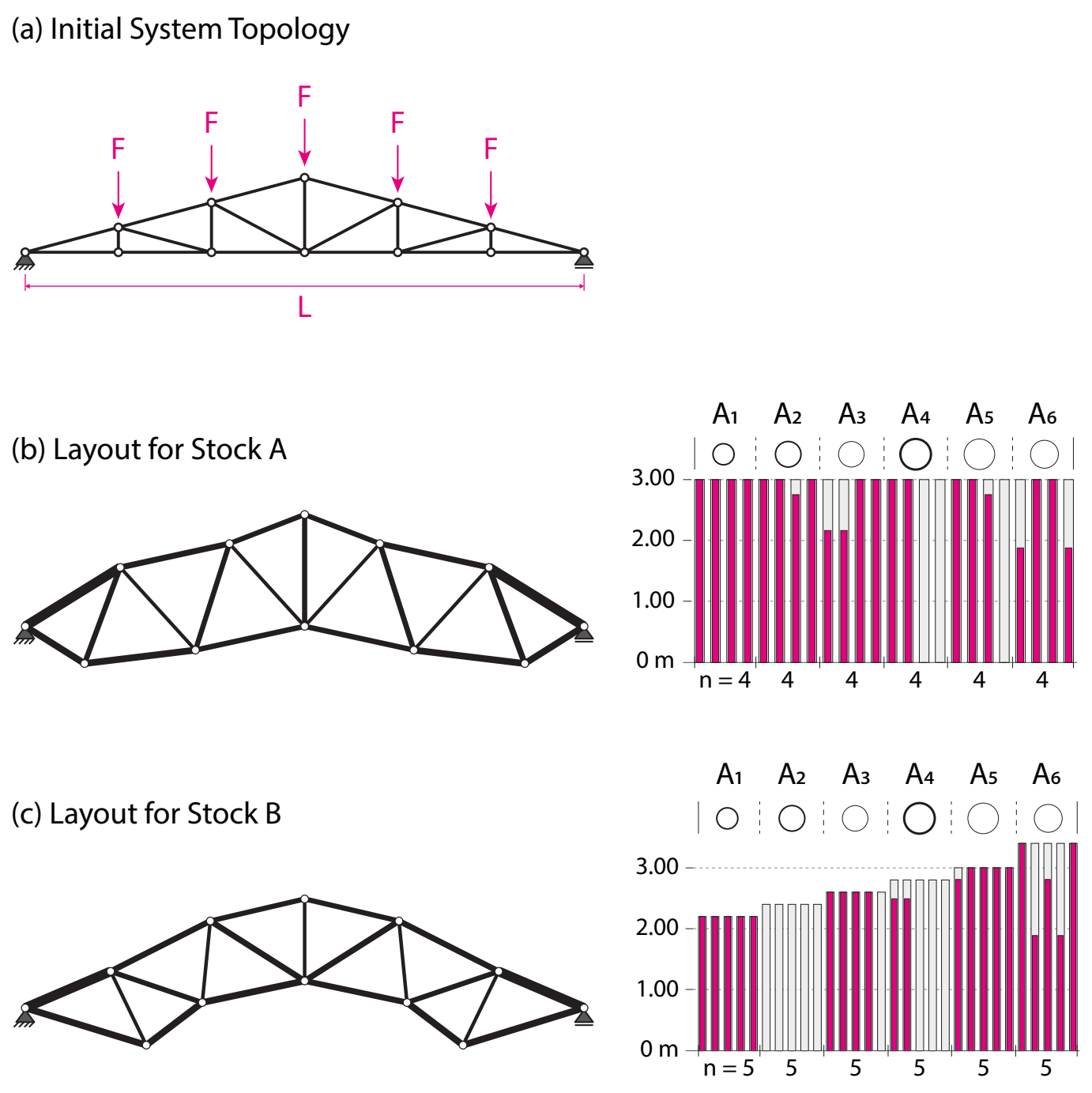

Fig. 5: Form findin results (a) Initial system, (b) optimum layout for stock A, and (c) for stock B

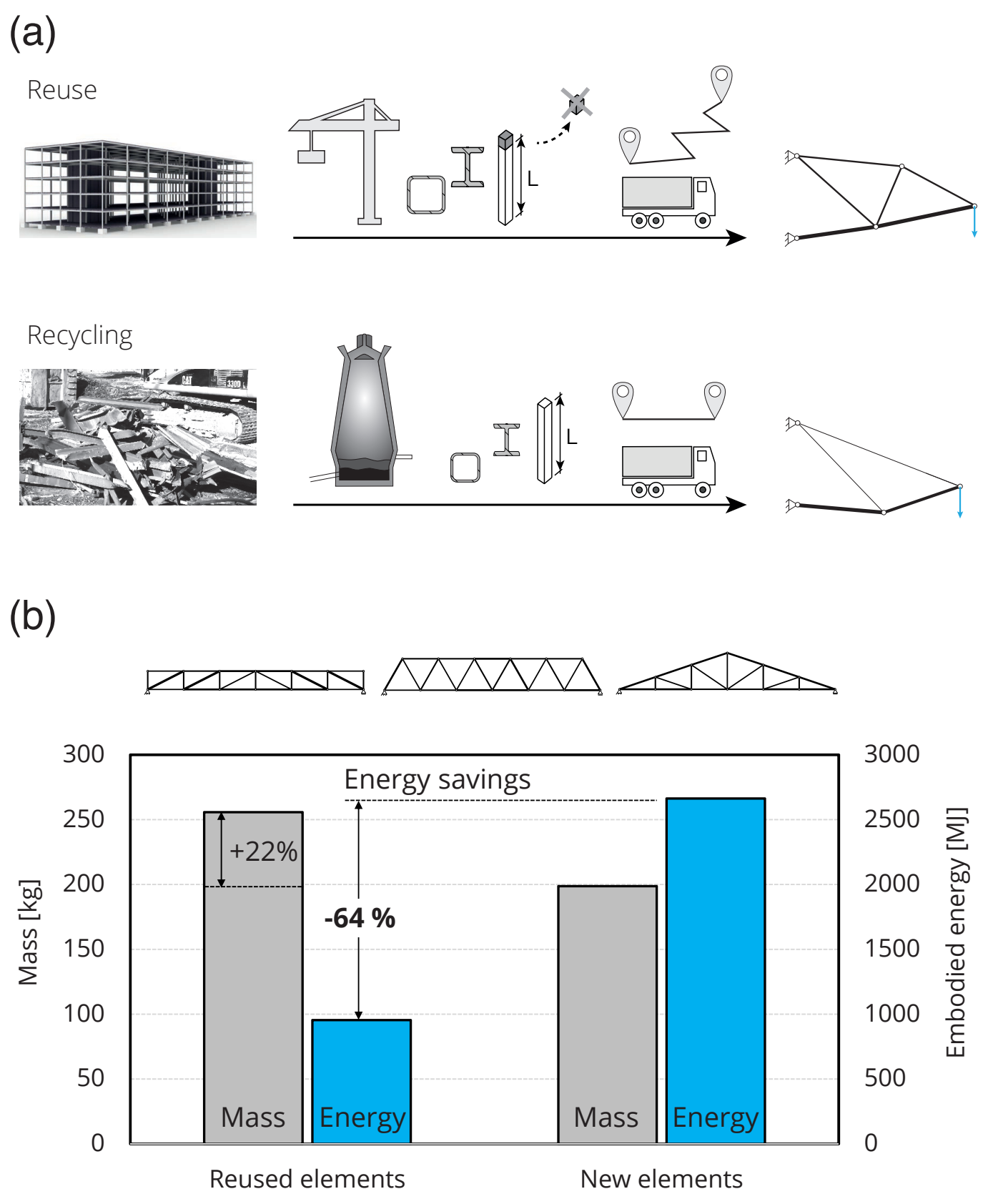

Fig. 7: Environmental impact comparison [2]

Fig. 4: Examples of structural element reuse: (a) Mezquita Cordoba, (b & d) Big Dig House, Boston, (c) crane bridge Brussels, (e) Olympic Stadium London, and (f) wooden bridge centrings

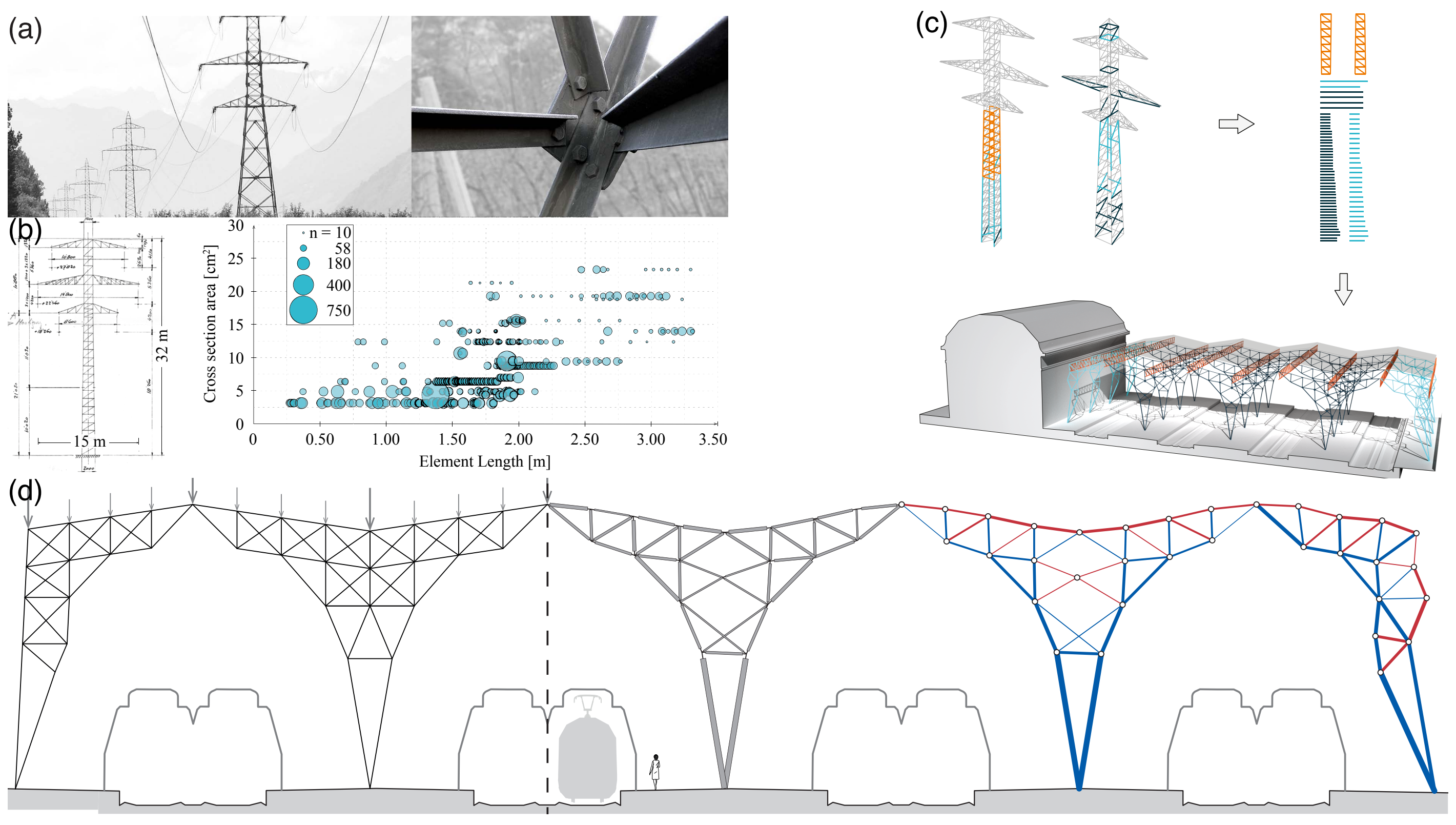

Fig. 6: Roof case study (a) reuse of transmition tower parts, (b) stock characterization, (c) design scheme, and (d) optimization results (left: initial topology and loads, middle: optimized layout, right: normal force pattern)

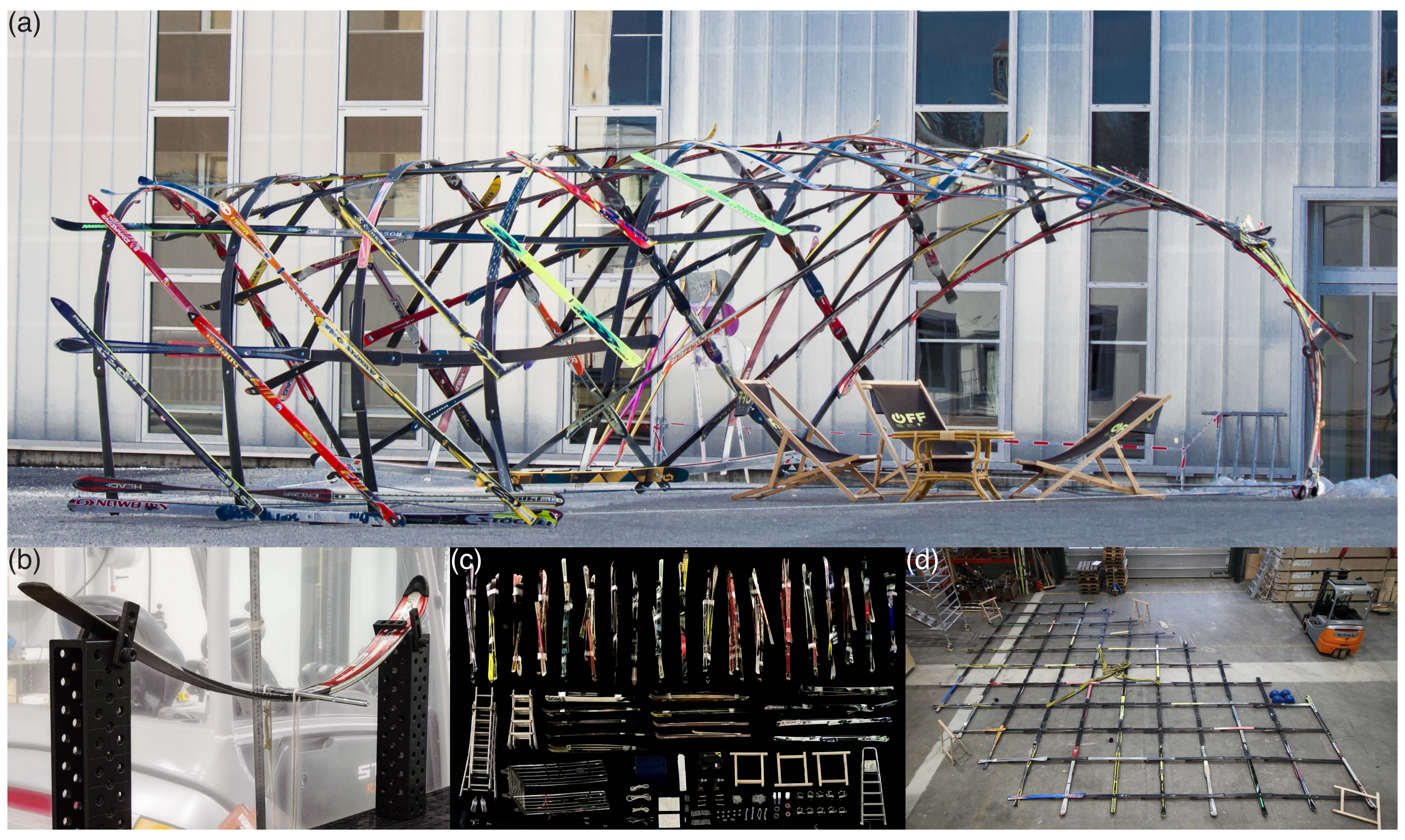

Fig. 8: SXL Ski Grid Shell: (a) bent grid shell pavilion, (b) ending stiffness testing, (c) kit-of-parts, and (d) flat grid