DOI: 10.1002/stab.202200019

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Steel, a material to reuse

Swiss steelweek+ 2021

The destructive impact of the construction industry on the planet and its inhabitants is no longer in question. Global warming, waste management, depletion of natural resources, air and soil pollution are all issues that must be urgently addressed. They are also challenging the current economy, whose growth is directly correlated to the extraction of raw materials, the manufacture of new products and, ultimately, to their increased consumption. Besides, the constant transformation of the built environment and infrastructure of a territory is a necessary lever for sustainable development and for guaranteeing the well-being of all. Faced with this situation, an emerging circular strategy could be salutary: component reuse, which makes it possible to build new assemblies without manufacturing new materials. Steel, if assembled with reversible means, is a particularly well-suited material for reuse. But are the stakeholders ready to adopt new business models?

Keywords reuse; circular economy; stock-based optimization; material efficiency; greenhouse gas emissions

Stahl, ein wiederverwendbarer Werkstoff

Die zerstörerischen Auswirkungen der Bauindustrie auf den Planeten und seine Bewohner sind inzwischen unbestritten. Der Klimawandel, die Abfallwirtschaft, die Verknappung der Bodenschätze, die Luft- und Bodenverschmutzung – all dies sind Themen, die dringend angegangen werden müssen. Sie stellen zudem eine Herausforderung für die derzeitige Wirtschaft dar, deren Wachstum in direktem Zusammenhang mit der Gewinnung von Rohstoffen, der Herstellung neuer Produkte und letztlich mit deren steigendem Verbrauch steht. Eine kontinuierliche Umgestaltung der bebauten Flächen und der städtischen Infrastrukturen ist ein unerlässlicher Hebel für eine nachhaltige Entwicklung und für die Wahrung des Wohlergehens aller Menschen. Angesichts dieser Situation könnte eine sich derzeit entwickelnde Strategie der Kreislaufwirtschaft von Nutzen sein: die Wiederverwendung von Bauteilen, die es ermöglicht, neue Gebäude zu errichten, ohne neue Baustoffe herzustellen. Stahl ist ein besonders gut geeigneter Werkstoff für die Wiederverwendung, sofern Bauteile reversibel montiert werden. Doch sind die Akteure bereit, neue Geschäftsmodelle zu übernehmen?

Stichworte Wiederverwendung; Kreislaufwirtschaft; Optimierung der Lagerhaltung; Materialeffizienz; Treibhausgasemissionen

1 A little reminder

There is no planet B and Earth's ecosystems are not doing well. The construction industry plays a big part in the equation. It is estimated that 50 % of the mass of materials produced in industrialized countries is destined for the construction sector [1]. Global demand for steel has doubled since 2000 [2] and, without major systemic change, will continue to increase as long as the world's population grows [3]. Meanwhile, the extraction and processing of raw materials actively contributes to global warming. It is estimated that 11 % of all annual anthropogenic carbon dioxide (CO_2) emissions worldwide are due to the production, maintenance and demolition of buildings [2]. More than two thirds of the volume of waste generated in Europe comes from demolition or construction sites [4]. The need for new buildings is constantly reiterated and existing buildings rarely reach their expected service life. The extension and densification of urban areas, the energy renovation of buildings, or more indirectly the typological adaptation of housing, offices and retails to emerging uses, imply a never-ending transformation or replacement of the built environment. At the territorial level, the constant modification of mobility, fluid and energy demands also leads to a continuous update of infrastructure networks.

2 The traditional toolkit

Traditionally, architects and structural designers pursue two strategies to minimize the environmental impact of their projects. The first strategy is to reduce the amount of material required for the project. Directly correlated to production costs, this strategy has always existed, whether we consider the structural performance of Thomas Telford's bridges, Jean Prouvé's systems or, more recently, the many algorithms for structural optimization. For regular building skeletons, the strategy consists, for example, in seeking the best placement of supports in relation to the spans that they create. The strategy also reconsiders the unneeded oversizing of the structural sections, often due to an excessive rationalization of the production and construction processes [5].

The second strategy, which is historically more recent, makes use of alternative materials, in particular those that are naturally abundant and, by extension, whose production generates fewer greenhouse gas emissions: biosourced or earth-based materials, materials that contain recycled content, or variants with reduced environmental impact. Contemporary steel, when derived from recycled steel scraps, falls in this category.

However, in view of the climate emergency, these two strategies have a limited impact as they do not decouple the demand for new materials from the demand for new constructions. A strategy to achieve such a decoupling – and one that only involves the responsibility of building designers – is to persuade clients that there is no need for new construction when existing buildings can provide the same programmatic objectives [6, 7]. However, the need for transforming the built environment remains, mainly in order to achieve greater occupant well-being or new sustainability objectives. It is in this more open perspective that the principles of the circular economy make sense.

3 The circular toolkit

The primary objective of a circular economy is to keep existing products in service as long as possible. Considering a building or part of a building as a product, the successive strategies consist, in priority order, of (1) using the product as much as possible, without physical modification, and adapting its use if there is a risk of obsolescence or an opportunity for increased intensity of use; (2) repair, renovate, maintain, or improve it in situ; (3) deconstruct it in whole or in part and reuse the disassembled components elsewhere with minimal transformation; (4) crush, shred or melt the material to produce new ones (recycling).

In the order given, it is expected that each strategy will have a less harmful environmental impact than the next one. Graphically illustrated, the succession of strategies creates overlapping and repeating loops, and explains how this economy is circular (Fig. 1). It circulates uses, operations and materials in order to limit new productions. Through new business models, the circular economy is a driver of local job creation. It also reduces dependency on imports.

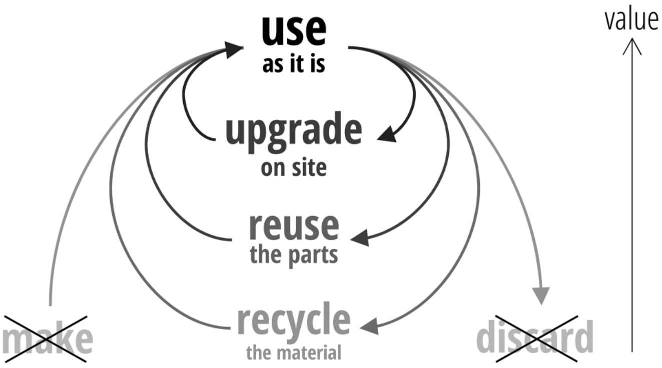


Fig. 1 Four complementary strategies for achieving a circular economy in the construction industry
Vier sich ergänzende Strategien zur Umsetzung einer Kreislaufwirtschaft im Baugewerbe

When a new production is deemed necessary, the viability and effectiveness of these four circular strategies will be guaranteed if the product is designed to be disassembled, thus favoring its future selective repair and deconstruction [8]. For steel connections, it mainly means that the use of bolts must be favoured over welding. If members are welded, technology for cutting parts on-site and drilling new connections are available. In addition, the probability of future reuse will increase if the new components can be used in a variety of arrangements, as shown on Fig. 2 where the definition of a kit of structural bars has been optimized to fit the need of three structures of diverse topology [9].

All these strategies, traditional or circular, are complementary to each other [10]. Each is necessary and none is sufficient to achieve environmentally sustainable objectives. For example: optimizing the cross-sections of a building structure would only allow a 40 % reduction in the total built mass [11]; recycled steel only reduces greenhouse gas emissions by a certain percentage compared to first-hand steel; and reuse and recycling are limited by the

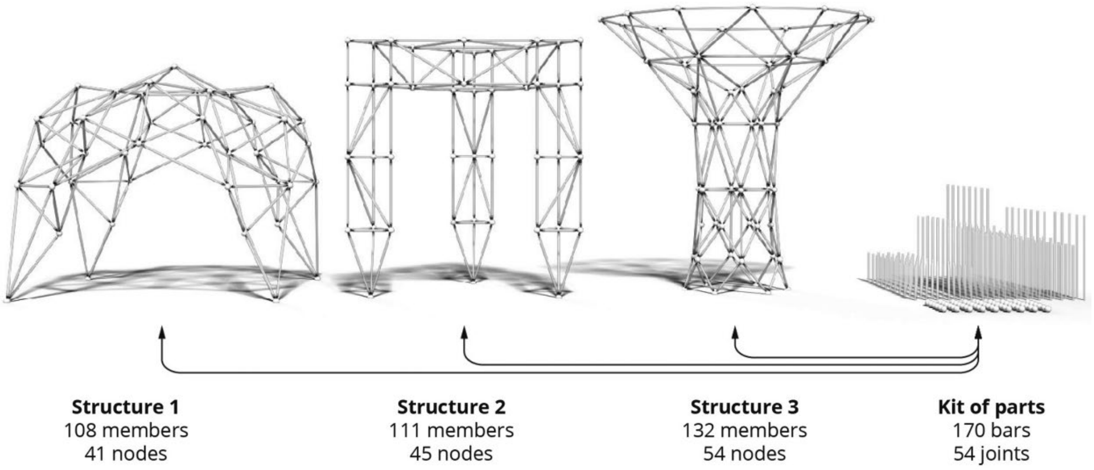


Fig. 2 Design of a kit-of-part to optimize the use of its elements in three different structure [9]
Entwurf eines Baukastens zur bestmöglichen Nutzung der einzelnen Bauteile in drei verschiedenen Tragwerken [9]

volumes of demolition, which are currently much lower than the volumes of new construction. There is no quick fix. All strategies must be considered and considering any of them is better than business as usual.

4 Component reuse and the necessary shift of design paradigm

Of all the circular strategies cited above, reuse is the one that is most alien to current practices. Yet this was far from being the case before the industrialization of construction, when production costs exceeded labor costs. Whether it is a one-hundred-year-old building frame (Fig. 3), twenty-year old ski lift cables (Fig. 4), steel-concrete composite slabs from a recently built temporary motorway bridge (Fig. 5), or steel columns and beams from a storage hall (Fig. 6), reuse extends the service life of components beyond the service life of the system in which they are used [12]. Reuse does not replace recycling but delays it. As detailed in the following paragraphs, reuse invites a complete paradigm shift in the design and construction of structures, with its opportunities and pitfalls.

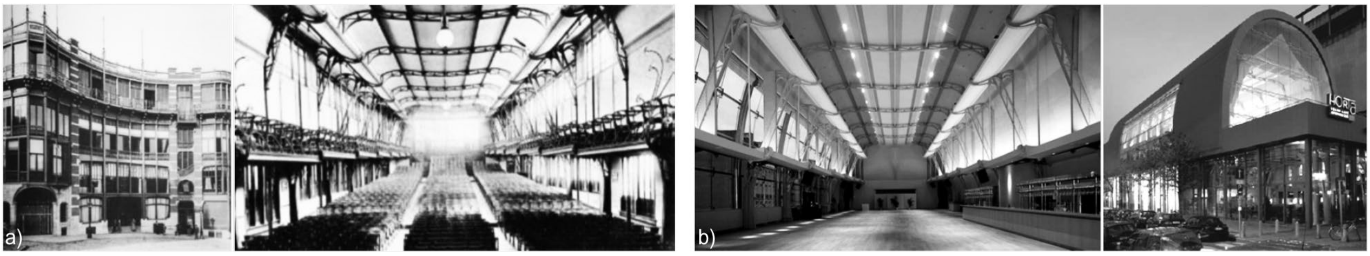


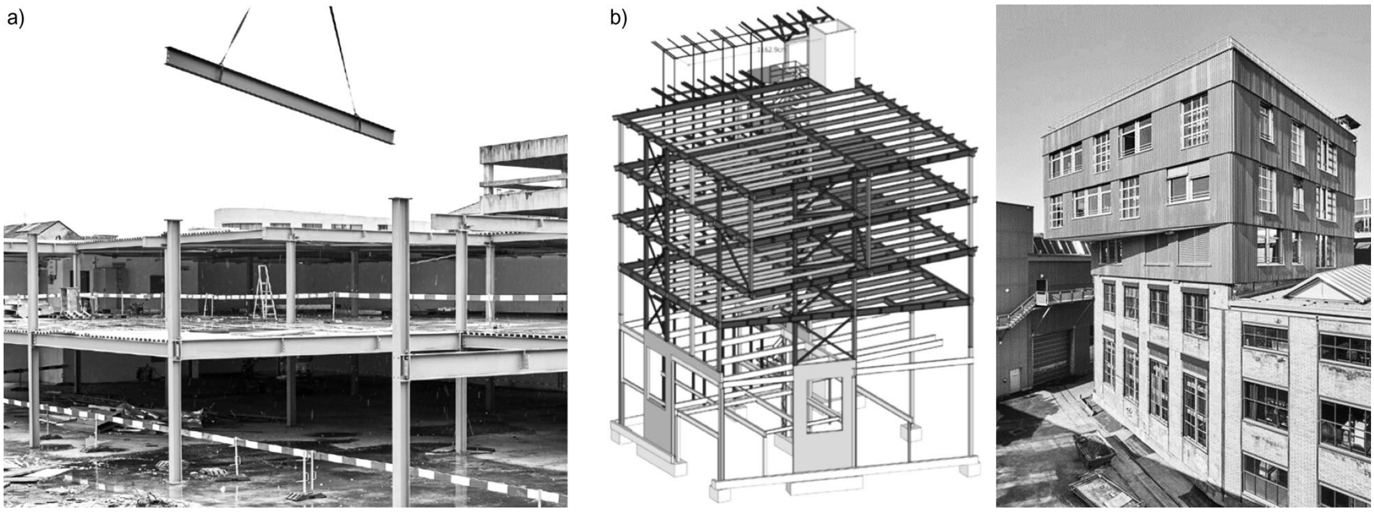
Fig. 3 Reuse of a building frame from the Maison du Peuple in Brussels, constructed in 1899 by architect Victor Horta and dismantled in 1966 (a), to a café in Antwerpen by Arrow architects, constructed in 2000 (b)
Wiederverwendung eines Rahmentragwerks aus dem Maison du Peuple in Brüssel, das 1899 durch den Architekten Victor Horta errichtet und 1966 abgebaut wurde (a), für ein Café in Antwerpen, das 2000 von Arrow architects realisiert wurde (b)

Courtesy of Toni Rüttiman

Fig. 4 Reuse of cables from ski lift installations in Switzerland (a) to suspension footbridges in Asia, by engineer Toni Rüttiman (b)
Wiederverwendung von Tragseilen aus Skiliftanlagen in der Schweiz (a) für Hängebrücken in Asien, durch Ingenieur Toni Rüttiman (b)

Courtesy of SSD Architecture

Fig. 5 Reuse of steel and concrete composite slabs from a temporary motorway bridge in Boston, MA (a) to a house in Lexington, MA in 2013 by architecture office Single Speed Design (b)
Wiederverwendung von Stahlbetonverbundplatten einer provisorischen Autobahnbrücke in Boston, MA (a) für ein Wohnhaus in Lexington, MA im Jahre 2013 durch das Architekturbüro Single Speed Design (b)



Courtesy of Baubüro In Situ

Fig. 6 Reuse of steel beams and columns from a discarded distribution centre (a) to the extension of an office building in Winterthur, by architecture firm Baubüro In Situ, completed in 2021 (b)
Wiederverwendung von Stahlträgern und -stützen aus einem stillgelegten Vertriebszentrum (a) für die Erweiterung eines Bürogebäudes in Winterthur, das 2021 vom Baubüro In Situ realisiert wurde (b)

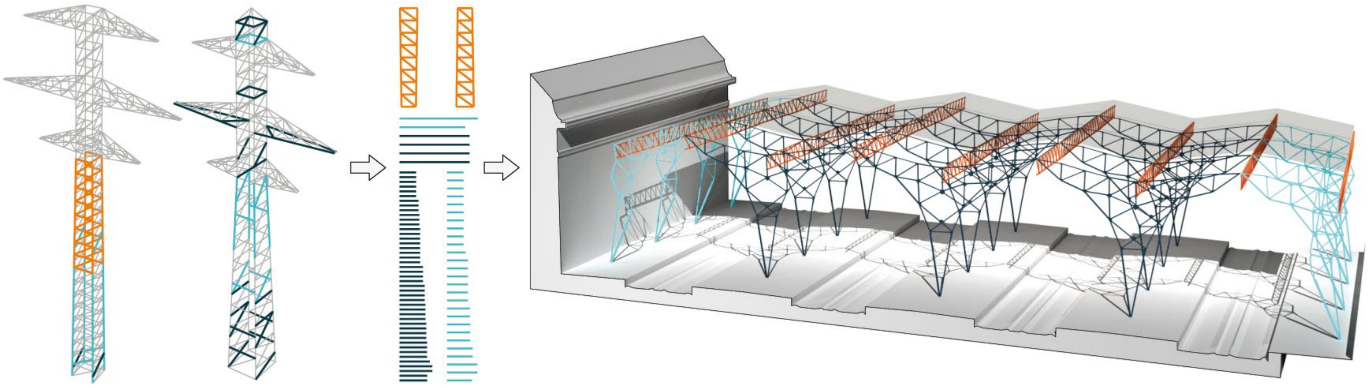


Fig. 7 Reuse of bars from obsolete electric pylons in a new roof structure for a train station: automated bar selection, structural form-finding, and bar assignment [13]
Wiederverwendung von Stabelementen ausgedienter Strommasten in einer neuen Dachkonstruktion für einen Bahnhof: automatische Stabauswahl, konstruktive Formfindung und Stabzuordnung [13]

Firstly, reuse offers designers the opportunity to reestablish an intimate dialogue with building materials, their features, their provenance, and their implementation. Far from standard catalogues and ready-made solutions, the stock to be reused requires special attention. It has a unique history and is varied. Each item of stock has its own mechanical and formal properties. It is a witness to a know-how that may have disappeared. Its reuse will make the most sense if the design work manages to take full advantage of the technology offered intrinsically by the component. Such attention can only improve the quality of the overall design and open up a new field of study for engineering. As an example, optimization tools have been developed recently to simultaneously automate the (-) selection of bar components worth being reused from a given stock, (-) the form-finding of a new structure that would best reuse those components, and (-) the best location of those components in the new structure (Fig. 7) [13, 14].

Secondly, it can be argued that the reused component is of better quality than a new one, provided that the new scope of the component is well framed. Buildings are nowadays generally considered obsolete, and therefore good for deconstruction, before their components are degraded or have reached their own lifespan. The reused component is therefore already tested by time and use, without having lost its quality. By combining conventional non-destructive testing methods with historic tables of steel grades, the performance and defects of the component to reuse are known beforehand. Structural analyses can be based on design assumptions that are as safe as for conventional processes.

Thirdly, the objective of reuse calls for the creation of new services and new dialogues between existing trades. Recent years have seen the emergence of a range of new professions in the construction industry: materials hunters, who scour the city for buildings to be dismantled; resource surveyors, who assess the economic interest in deconstructing and reusing a particular component of a building prior to its demolition; matchmakers, who bring together offers and requests for reuse between construction sites or stakeholders; deconstructors, who are

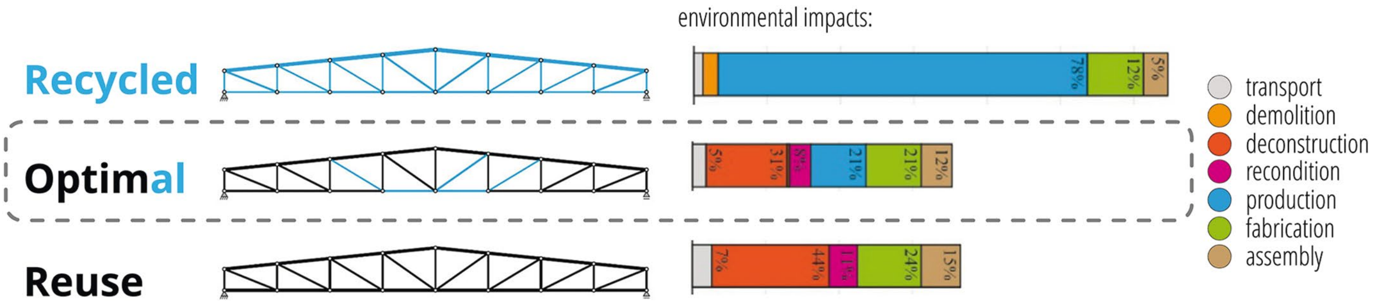


Fig. 8 Comparison of environmental impacts between three scenarios: all bars are made of recycled steel (top), all bars are reused from existing stocks (bottom), and an optimum selection of recycled and reused bars is found (middle) [15]
Vergleich der ökologischen Auswirkungen dreier Szenarien: Alle Stäbe werden aus recyceltem Stahl hergestellt (oben), alle Stäbe werden aus vorhandenen Beständen wiederverwendet (unten), es wird eine optimale Verteilung von recyceltem und wiederverwendetem Stahl ermittelt (Mitte) [15]

able to recover components without damaging them; cataloguers of craftpersons and contractors capable of repairing or upgrading components resulting from deconstruction; companies producing – and possibly managing the stock of – reversible and highly reusable construction solutions; project managers providing expertise in circularity; certifiers of used materials.

Several studies [13, 15–17] show that reuse of steel can drastically reduce the environmental footprint of new reticulated structures, up to 60 % on average, provided that the distances between sites remain under control [15]. These gains are generally accompanied by an increase in the mass of the structure, explained by the fact that the reused sections are oversized. This increase in structural mass, in the case of steel trusses, still has a negligible impact compared to the larger applied loads. However, if the goal is to decrease environmental impacts to a minimum, it makes sense to replace the most oversized reused members with newly manufactured bespoke elements, as confirmed in [15, 16] (Fig. 8). From a more general point of view, this result suggests that a dogmatic approach seeking 100 % reuse is not ideal as it can lead to additional environmental costs that can be easily avoided by introducing a few new elements. The reflection can be extended by considering the additional economic costs. In this respect, it is important to point out that the few recent large-scale building reuse projects have a financial balance sheet close to that of conventional projects, with losses or profits remaining within a range of +– 15 %, which is promising given that these projects are developed in an economic context that is far from being optimized for circularity.

Achieving a high level of environmental and structural quality through reuse is not systematic and requires special attention from designers. For instance, there is always a risk of premature downcycling when reusing a component. Downcycling occurs when the new use does not take advantage of all the qualities and functions offered by the component, which prevents the component from being reused elsewhere where it would be more useful or reach a higher performance. The notions of use and downcycling are central to the assessment of the quality of a reuse project. Yet, they are very difficult to quantify and compare objectively, which makes circularity assessments by legislators and labels harder. Can the actual value of a reuse strategy be measured? Probably not. This suggests that critical (and subjective) analyses of built projects will have an important role to play in developing the discipline of reuse and in establishing its canons, as has always been the case in architecture and structural design.

A lack of reliable method for evaluating the quality of a reuse practice may also present a risk of pollution shift, i. e. a transfer of the environmental impacts avoided by reuse – e. g. by avoiding the production of new material – to other processes generated by reuse – e. g. too long transport distances or too complex connection details. There is also a risk of ‘wishcycling’, i. e. a process in which the desire to ‘do the right thing’ for the environment is genuine on the part of designers but the environmental gains are in fact anecdotal or non-existent. There are also risks associated with difficult upfront control, whether it be cost control, expected mechanical quality, aesthetics of components and their assembly, guaranteed supply, or management of the stock variety. However, all these risks are expected to be safely and efficiently managed by adapting conventional design processes.

In the end, the real questions whose answer will define whether reuse is a life-saving strategy or an eternal utopia is whether reuse can exist beyond a niche practice, i. e. whether reuse can become as commonplace as it was before the industrial revolution. There are reasons to believe so, but it remains to be proven.

5 Conclusions

Today’s markets and design practices are far from being optimized to allow the reuse of steel parts in new structural applications. Yet, this circular strategy has the potential to greatly reduce greenhouse gas emissions, material depletion and waste generation worldwide, since it avoids the manufacturing of new pieces and delays the recycling of unwanted material. From a technological point of view, steel constructions are particularly suited for allowing the large-scale reuse of their components.

The main reason why reuse is not more widespread today might be only related to the lack of publications on successful design experiments and proven business cases. Indeed, the fear of the unknown, together with the well-known inertia of the construction industry towards innovation, might be the only real barriers preventing the full implementation of a circular economy. It is therefore every stakeholder's responsibility to explore, implement and validate new ways to overcome these barriers as quickly as possible, faster than climate change.

References

[1] Herczeg, M.; McKinnon, D.; Milios, L.; Bakas, I.; Klaassens, E.; Svatikova, K.; Widerberg, O. (2014) *Resource efficiency in the building sector (Final Report)*. European Commission, DG Environment, Rotterdam.

[2] International Energy Agency (2019) *Material Efficiency in Clean Energy Transitions, Paris* [online]. www.iea.org/publications/reports/MaterialEfficiencyinCleanEnergyTransitions

[3] United Nations, Department of Economic and Social Affairs, Population Division (2017) *World Population Prospects: The 2017 Revision, Key Findings and Advance Tables*. Working Paper No. ESA/P/WP/248. Cite Sarja. On life-cycle design.

[4] Eurostat (2018) *Waste statistics* [online]. http://ec.europa.eu/eurostat/statistics-explained/index.php/Waste_statistics [visited on Feb. 15, 2018]

[5] Orr, J.; Drewniok, M. P.; Walker, I.; Ibell, T.; Copping, A.; Emmit, S. (2019) *Minimising energy in construction: Practitioners' views on material efficiency*. Resources, Conservation & Recycling 140. pp. 125–136. https://doi.org/10.1016/j.resconrec.2018.09.015

[6] Norman, J.; Ibell, T.; Broadbent, O. (2020) *How can we create an engineering industry while building nothing?* The Institution of Structural Engineers 98, no. 7, pp. 31.

[7] Ibell, T.; Norman, J.; Broadbent, O. (2020) *Nothing is better than something*. The Institution of Structural Engineers 98, no. 6, pp. 12.

[8] Küpfer, C.; Fivet, C. (2021) *Déconstruction sélective – Construction Réversible: recueil pour diminuer les déchets et favoriser le réemploi dans la construction*. Swiss Federal Office for the Environment Series. http://doi.org/10.5281/zenodo.4314325

[9] Brütting, J.; Senatore, G.; Fivet, C. (2021) *Design and fabrication of a reusable kit of parts for diverse structures.* Automation in Construction 125, 103614. http://doi.org/10.1016/j.autcon.2021.103614

[10] iStructE (2021) *Sustainability Resource Map* [online]. https://www.istructe.org/IStructE/media/Public/Resources/IStructE-Sustainability-Resource-Map.pdf

[11] Dunant, C. F.; Drewniok, M. P.; Eleftheriadis, S.; Cullen, J. M.; Allwood, J. M. (2018) *Regularity and optimization practice in steel structural frames in real design cases*. Resources, Conservation & Recycling 134. https://doi.org/10.1016/j.resconrec.2018.01.009

[12] Fivet, C.; Brütting, J. (2020) *Nothing is lost, nothing is created, everything is reused: structural design for a circular economy*. The Structural Engineer 98, no. 1, pp. 74–81.

[13] Brütting, J.; Desruelle, J.; Senatore, G.; Fivet, C. (2019) *Design of Truss Structures Through Reuse*. Structures 18, pp. 128–137. http://doi.org/10.1016/j.istruc.2018.11.006

[14] Warmuth, J.; Brütting, J.; Fivet, C. (2021) *Computational tool for stock-constrained design of structures* in: Behnejad, S. A.; Parke, G. A. R.; Samavati, O. A. [eds.] *Proceedings of the IASS Annual Symposium 2020/21 and 7th International Conference on Spatial Structures*. Guilford, UK, Aug. 23–27, 2021, pp. 1–9.

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

[16] Brütting, J.; Senatore, G.; Schevenels, M.; Fivet, C. (2020) *Optimum design of frame structures from a stock of reclaimed elements*. Frontiers in Built Environment 57, no. 6, pp. 1–18. https://doi.org/10.3389/fbuil.2020.00057

[17] Küpfer, C.; Bertola, N. J.; Brütting, J.; Fivet, C. (2021) *Decision Framework to Balance Environmental, Technical, Logistical, and Economic Criteria When Designing Structures With Reused Components*. Frontiers in Sustainability 2, 689877. http://doi.org/10.3389/frsus.2021.689877

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How to Cite this Paper

Fivet, C. (2022) *Steel, a material to reuse.* Stahlbau 91, H. 4, S. 268–273. https://doi.org/10.1002/stab.202200019