PREPRINT

Sustainability ≡ Circular economy

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Nothing is lost, nothing is created, everything is reused: structural design for a circular economy

SYNOPSIS

Structural designers' efforts to reduce environmental impacts traditionally consist of developing systems that minimise material quantities or use low-impact materials. A third strategy is currently (re)emerging: the reuse of structural components over multiple service lives and in new layouts.

Still in its infancy, this circular economy strategy disrupts structural design practice in many ways: rather than manufacturing components after the design of a system, the system is synthesised from a given stock of reclaimed components; versatility, reversibility and transformability become hard requirements for all loadbearing systems and components; costs, performance and environmental assessments span multiple service lifecycles.

There is consequently a sudden lack of expertise, design tools, technological solutions and relevant metrics. This article contextualises the effects of the circular industrial economy upon structural design practice and reviews recent and future developments in the field.

FIGURE 1: Three strategies to lower product's environmental footprint over its lifespan

Introduction

'Nothing is created, nothing is lost, everything is transformed.' The conservation principle was already well understood by ancient Greek philosophers[1]. As were the earth's sphericity and meteorology. All together, the three notions put humanity in a closed world of finite resources and fragile atmospheric equilibrium. 'Spaceship Earth'[2] crystallised more than 2000 years later when NASA widely published its integral picture of the planet from space in 1972. Today, environmental consciousness is taking on new dimensions and justifies the search for a reshaped future.

Embodied carbon in buildings – i.e. CO_2 emissions related to component manufacture, construction, renovation and end-of-life – accounts for 11% of the overall annual energy- and process-related CO_2 emissions worldwide. The global annual steel and cement demand currently amounts to 2.5 gigatons, which is twice that of 2000[3]. Construction and demolition waste is the largest waste stream by volume in the EU, making up about a third of all waste produced[4].

The world population is expected to increase to almost 10bn people by 2050. In 2008, for the first time in history, over half of the world's population lived in urban areas, and by 2050 this will have risen to 70%[5]. Growth and densification of urban areas lead to the rapid demolition, transformation and construction of a tremendous amount of residential, industrial and community buildings plus the necessary infrastructure. The need to reduce greenhouse gas emissions, raw material depletion, and construction and demolition waste is pressing.

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January 2020 | thestructuralengineer.org

Please cite this work as:

Corentin FIVET and Jan BRÜTTING, Nothing is lost, nothing is created, everything is reused: structural design for a circular economy, *The Structural Engineer*, vol. 98(1), p. 74-81, 2020

Link to publisher.

Nothing is lost, nothing is created, everything is reused: structural design for a circular economy

Synopsis:

Structural designers' efforts to reduce environmental impacts traditionally consist in developing systems that minimise material quantities or that use low-impact materials. A third strategy currently (re)emerges: the reuse of structural components over multiple service lives and in new layouts. Still in its infancy, this circular economy strategy disrupts the structural design practice in many ways: rather than manufacturing components after the design of a system, the system is synthesised from a given stock of reclaimed components; versatility, reversibility, and transformability become hard requirements for all load-bearing systems and components; costs, performance, and environmental assessments span multiple service life cycles. There is consequently a sudden lack of expertise, design tools, technological solutions, and relevant metrics. This article contextualises the effects of the circular industrial economy upon the structural design practice and reviews recent and future developments for the field.

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Introduction

« *Nothing is created, nothing is lost, everything is transformed* ». The conservation principle was already well understood by ancient Greek philosophers[1]. As were the earth's sphericity and meteorology. Altogether, the three notions put humanity in a closed world of finite resources and fragile atmospheric equilibrium. *Spaceship Earth*[2] crystallised more than two thousand years later when the NASA widely published its integral picture of the planet from space in 1972. Today, environmental consciousness takes on new dimensions and justifies the search for a reshaped future.

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Traditionally, structural designers address environmental challenges by conceiving systems with minimised material quantities or low environmental impact materials. On the one hand, weight minimisation under serviceability and strength constraints has been a customary objective function throughout the history of civil engineering. On the other hand, the field also pursues an endless quest towards the engineering and manufacturing of higher-performance structural materials (e.g. high-strength steel and concrete or structural composites) or renewable ones (e.g. timber or rammed-earth). Despite all current efforts, the environmental impact of the construction industry remains an urgent concern and additional means must be found to alleviate it.

A third strategy (Figure 1) consists in delaying the obsolescence of manufactured structural components, by ensuring the long-term usefulness of the structural system put in place and/or, once the system is deemed obsolete, by repurposing its components in new layouts. The task before structural designers is to ensure that components can be kept in use as long as possible, either in the initial context for which they were designed or in future unforeseen contexts. In other words, nothing is lost, nothing is created, everything is reused, at minimal environmental (and economical) cost. This strategy is considered key to achieve a *circular industrial economy*.

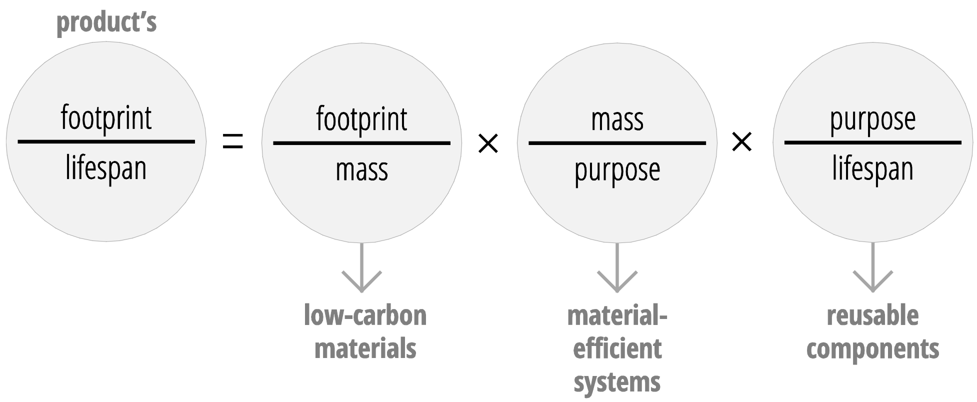

Figure 1. Three strategies to lower a product's environmental footprint over its lifespan.

Although reuse is not new in the history of structural engineering, its systematic adoption by today's design practice causes a shift of paradigm at various levels: rather than manufacturing components after the design of a system, the system is synthesised from a stock of reclaimed components; versatility, reversibility, and adaptability become hard requirements for all load-bearing systems and components; costs, performance, and environmental assessments span multiple life cycles. There is consequently a sudden lack of expertise, design tools, technological solutions, and relevant metrics.

This article is an attempt at describing what the structural design practice will look like in a context of systematic and global adoption of a circular economy.

Circular Economy and Structural Engineering

A circular economy maximises product use lifespan by introducing loops of reclamation. It comes in contrast with the more common linear 'make-use-dispose' economy. From linear to circular, the focus shifts from value creation to value preservation and from throughput maximisation to waste minimisation. The nearly 40-years old theoretical concept[6] has since then been nudged in different directions by scholars[7,8], implemented as business model by some companies, and supported by governmental policies[9,10,11]. It is recognised as a means towards market innovation, job creation, and ultimate sustainability[12,13].

The application of a circular economy into the construction industry has not taken-off yet. Involving many stakeholders and dimensions, it opens up opportunities and requires breaking through a series of known systemic barriers[14,15,16,17,18]. In this paper, the focus is placed on structural designers and their own practice.

At the product level, a series of strategies exist to implement a circular industrial economy, see for instance the '9Rs'[19]:

1) *refuse*, i.e. prevent the use of raw materials
2) *reduce* the use of raw materials

3) *reuse*, i.e. employ second-hand or shared products
4) *repair* and maintain
5) *refurbish*
6) *remanufacture*, i.e. create new products from (parts of) old products
7) *repurpose*
8) *recycle*, i.e. reprocess the material through mechanical or chemical transformations
9) *recover* energy

The description of these strategies rarely fits with the peculiar nature of structures. Indeed, structural systems differ in that they are generally anchored on the ground for a long time and are produced in two phases: off-site manufacture and onsite construction. Besides preventing and reducing the use of raw materials, the set of strategies to extend the service life of structural components encompasses, in order of priority, Figure 2:

(1) *onsite reuse*, i.e. keep parts in use in their original system (renovation, repurposing);
(2) *repair*, maintain, or refurbish;
(3) *offsite component reuse*, i.e. disassemble components from their system and reuse them in new systems;
(4) *reprocess/recycle* the material, or remanufacture the component.

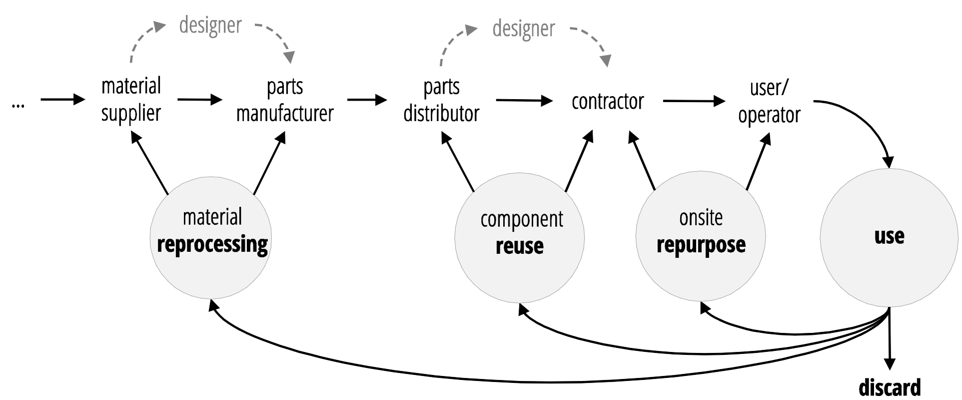

Figure 2 Introducing loops in the service life of structural components.

Product reuse is generally characterised by a change of owner, function, and/or location. A clear distinction exists between reuse (3) and recycling (4). In comparison to recycling, reuse avoids applying physical and chemical transformations to the material, as much as possible. Whereas recycling generates a new product from scrap, reuse reclaims the given product as it is while leveraging the most out of all its pre-existing mechanical and geometrical features. From one use cycle to the next, the added value of reuse merely consists in the definition of a new purpose for the given obsolete product. For those reasons, reuse is assumed to be less energy-intensive than recycling and should therefore be prioritized over recycling.

Strategies (1), (2), and (4) are already common practice and well understood. On the contrary, the reuse of load-bearing components in new contexts (3) is seldom. Its absence is illustrated best on Figure 3. The Twentec Towers (Enschede, the Netherlands) are two office buildings from the 1960s[20]. A major redefinition of the neighbourhood in the 2000s led to the demolition of one of the two towers, the other one being transformed into a residential building. The operation showcases both economic values of maintaining a load-bearing system in place and demolishing it. It also illustrates the rapidity at which functional requirements for building skeletons evolve: the load-bearing system of the demolished building became obsolete after less than forty years. Yet, the same load-bearing system is deemed structurally safe and remains useful in the other building for a substantially longer service life[21].

Structural products are generally meant for a very long lifespan in comparison to other building products. Whereas long-term material degradation can be a major issue for reuse, buildings are actually too often demolished before they present safety issues or a decrease in structural performance[22]. Instead of a design leading to an inevitable demolition, circular economy calls for a reversible design allowing disassembly and reassembly in new buildings.

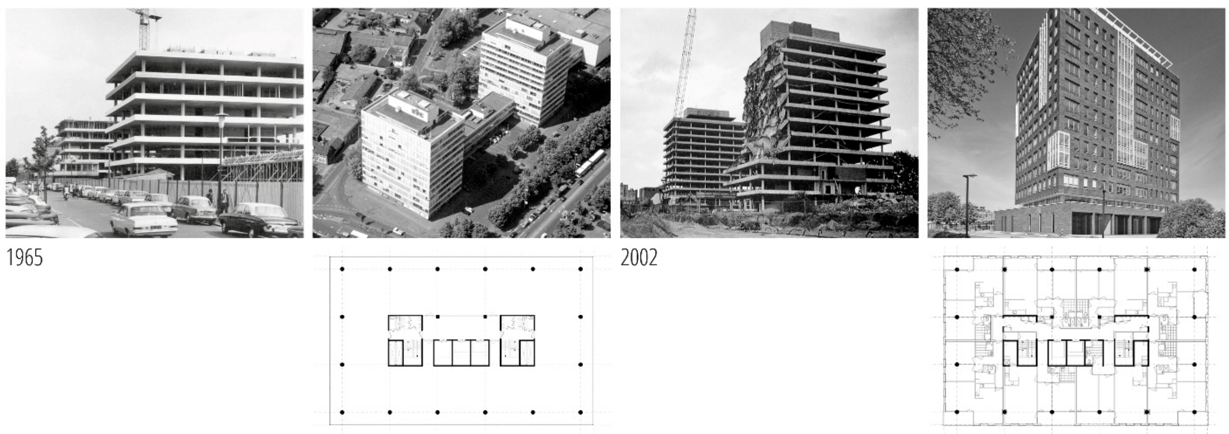

Figure 3. Demolition of an obsolete building skeleton although its parts remain fully functional[20]. Image Courtesy: Hilde Remøy and Paul Hofstee

Precedents

Designers can influence the effective lifespan of structural components in two ways: when reusing a discarded component in a new design; or when designing a new component and its assembly for future reuse. Respectively, reuse happens either *upstream* or *downstream* of the building service life being designed.

Upstream component reuse

Design for upstream component reuse consists in mining construction materials from former buildings or infrastructure. It was common practice prior to the industrial revolution because it was more cost and time efficient than new production. After the industrial revolution, production costs decreased, labour costs rose, non-reversible connections appeared, and reuse consequently became more sporadic. Today, very few accounts of component reuse are known by practitioners and construction historians[15,23,24,25,26,27,28]. More enquiries into precedents are needed in order to help the reuse practice gain more confidence and systematism.

In the 8th Century in Cordoba, Spain, nearby ruins of Roman and Visigoth buildings provided the 142 marble columns supporting the Moorish double arches inside the *Mezquita*[29]. Much more recently, donated cables from ski lifts or oil companies were reused in bridges of up to 260 m span in Honduras, Cambodia, and Myanmar[30], Figure 4. In both these cases, structural safety of the reclaimed material was implicitly checked because (a) the new utilizations of stone compression and cable tension capacities are not greater than the original ones, and (b) the components are reused in their original geometry and function.

Figure 4. Pedestrian bridge in Myanmar (right) built with cables from donated second-hand cables (left). Image courtesy: Toni Rüttimann.

In 1919, massive oak and spruce members of a 109-year-old timber bridge in Eglisau, Switzerland, were dismantled[31] and reassembled for the construction of a new barn nearby in Rheinau, Switzerland, Figure 5. The original members were well protected from moisture and it can be assumed that their strength could safely be approximated via visual grading. Today, the barn is 100 years-old while its components are more than 200 years-old. More recently, coupons of original material have been consistently tested in order to reintegrate 2'500 tons of pipeline tubes into the roof truss of the 2012 London Olympic Stadium[32].

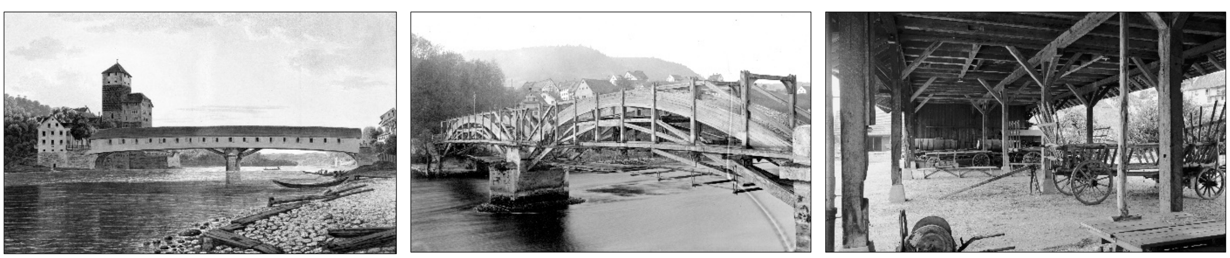

Figure 5. 100 years-old barn constructed with 200 years-old members reclaimed from nearby timber bridge. Left image: Painting by Franz Hegi, 1811-1829, Zentralbibliothek Zürich; middle and right images: Fotoarchiv kantonale Denkmalpflege Zürich.

Downstream component reuse

Design for downstream component reuse consists in crafting structures for easy repair, replacement, disassembly, transport, and eventual reassembly. To ensure the future reuse of load-bearing elements at the time of design implies the satisfaction of manifold requirements[33]:

(1) Durable manufacturing and construction
(2) Versatile layout to delay its obsolescence
(3) Reversible connections to allow for disassembly and reassembly

(4) Modular elements to ensure interchangeability and partial replacement
(5) Transformable systems to accommodate new spatial layouts or design loads, i.e. new purposes

Because of tight constraints on geometry or load path, a reversible system might be neither modular nor transformable, Figure 6 left. Also, a modular system might be neither reversible nor transformable, e.g. due to mortar assembly, Figure 6 centre. And finally, a transformable system might be neither modular nor reversible, e.g. transformation obtained by further carving, Figure 6 right. Satisfying only one of the requirements is therefore not sufficient to ensure reusability.

Figure 6. Reversibility (left, Vis de St-Gilles, Gard, France), modularity (centre, Parroquia del Cristo Obrero by Eladio Dieste, Uruguay), and transformability (right, Magdalena Hermitage, Switzerland) as three independent requirements. Left picture by Hawobo, centre picture by Andrés Franchi Ugart., right picture by Jan Brütting.

On the other hand, the satisfaction of all five requirements may still not guarantee the effective reusability of the components. Reusability will be more or less ensured depending on whether future functional and technical requirements are 1) easily foreseeable at the time of design, or 2) completely unpredictable. The first category contains most vernacular construction (both sedentary and nomad) as well as kit-of-part structures for entertainment or military activities. For instance, in 1921, the same wooden logs have been used to build the scaffolding of two different bridges in Fribourg, Switzerland[34]. Logs only had two different cross section sizes and were connected with bolts of only a single size.

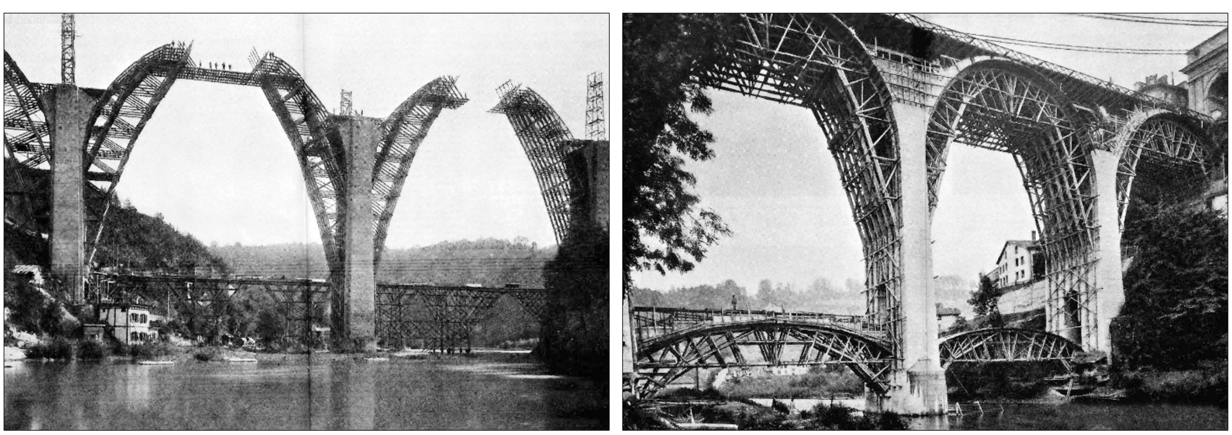

Figure 7. Same timber elements used for both centrings of the Pérolles (left, 1921) and Zärhingen (right, 1924) bridges, Fribourg, Switzerland. Image courtesy: Fonds Bourgarel - ProFribourg

The second category mainly concerns structural skeletons for office and residential buildings. For instance, the AgroResearch Campus in St-Aubin (Switzerland)[35] was built in 1969 with prefabricated, modular, concrete elements that are maintained in place by pure compression contact, which was meant for allowing the spatial reorganization of the campus in the long-term, Figure 8. Yet, the tectonics of the elements are too specific and their assembly can only create spaces with very similar use features[33].

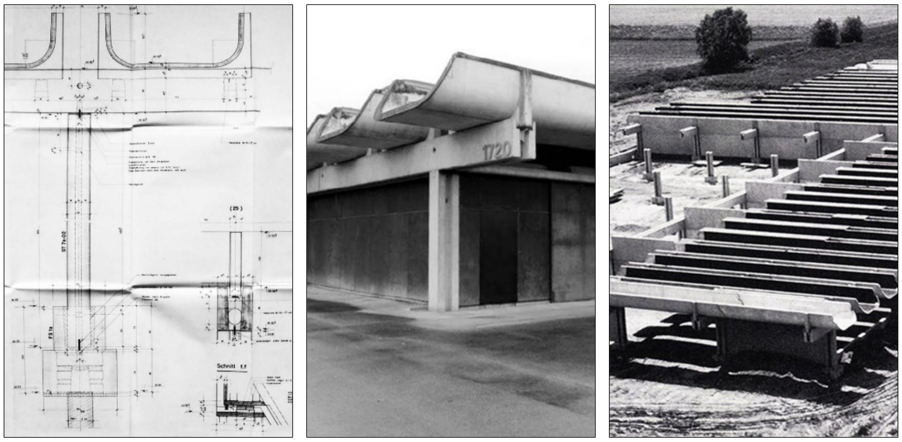

Figure 8. Reversible but hardly reusable reinforced concrete system at the AgroResearch Campus, St-Aubin, Switzerland, 1969, Jakob Zweifel.

Future developments

Except for vernacular construction, all historic examples of reuse are very specific to isolated experiments and often result from fortuitous opportunities. Because of growing environmental concerns, the strategy is currently resurfacing in a number of practices. However, efforts will only be meaningful if the reuse of load-bearing components is eventually implemented systematically and on a large industrial scale. The shift of paradigm will potentially alter the practice of structural design on various aspects: procurement, design process, construction technology, and environmental assessment. The following sections profile each of these developments.

Procurement: the rise of the material hunter

Considering the overall structural design process, reclamation merges two traditionally separated steps: conceptual design and material procurement. As both steps are carried out simultaneously, the designer becomes a ‘material hunter’ (or ‘urban miner’) and material stocks are secured prior to design specifications. Such new job description was created by the architecture office *baubüro in situ* during the conceptual design for the extension of the *Halle 118* in Winterthur, Switzerland, Figure 9. The task is to discover future demolition sites in the area, visit them, identify potentially reusable components, organize their purchase, dismantle, store and eventually catalogue them to allow their use in future buildings. The proximity between the material hunter and designers ensures an efficient live readjustment of supply and demand.

Physical reclamation outlets and web-based information platforms for construction materials have recently been launched and diverging business models are tested in different parts of Europe. Their mitigated success is probably due to (a) designers being reserved towards reuse and (b) demolition companies not having reskilled into non-destructive disassembly yet. The generalization of material passports and Building Information Models will bring more confidence in reclaimed properties[36], which would boost material hunting.

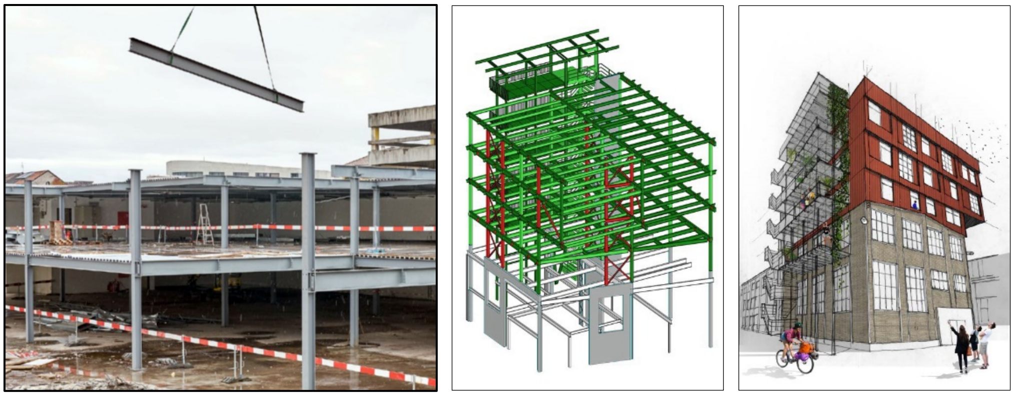

Figure 9. Project for a building extension (Halle 118, Winterthur, CH) sourcing steel beams and columns from a distribution centers. Image courtesy: Baubüro in Situ.

Waste material can also be diverted from outside the construction industry, which for instance, makes great sense for high-performance composites that are hardly recycled. For instance, the unique bending properties of skis make them suitable to replace timber laths in elastic gridshells[37], Figure 10. Other not-yet-discovered reclamation flows may lead to new market opportunities for structural engineers.

Figure 10. Elastic gridshell constructed with 210 reclaimed skis, EPFL, Switzerland[37].

Design process: switching inputs and outputs

As sketched on Figure 11, the reuse of reclaimed structural components entails a particular challenge and change of paradigm in structural design: elements characteristics, e.g. cross sections, strengths, lengths, and joint details, become inputs of the design process; the system geometry and topology form the output. Different to conventional design, this reversed process is not yet supported by design guidelines and tools. Computational techniques have recently been developed to (a) optimize the assignment of stock elements within an emerging system layout and (b) optimise the structure geometry, i.e. the node coordinates, to best-fit the geometric properties of the assigned elements and to reduce cutting and waste[38].

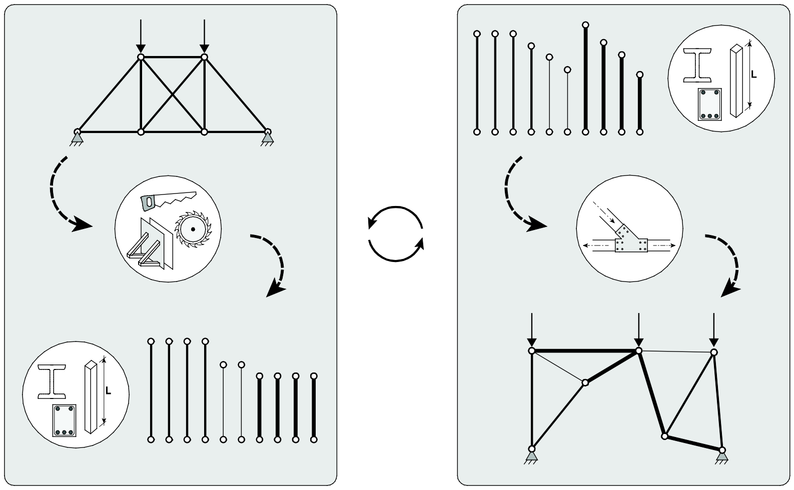

Figure 11. Reuse implies a reverse design process in which stock elements are the input for the design of the system.

For steel structure case studies, e.g. Figure 12, optimization provides solutions that have up to 70 % lower environmental impact than minimum-weight structures made from newly produced elements with recycled content[38]. However, structures made from reused elements become heavier and oversized when the availability of appropriate cross sections is limited[38], calling for larger foundations and heavier transport from site to site. This contrasting conclusion advocates for the design of hybrid solutions where structures are made of both reused and newly produced elements, in order to minimize both environmental impact and oversizing.

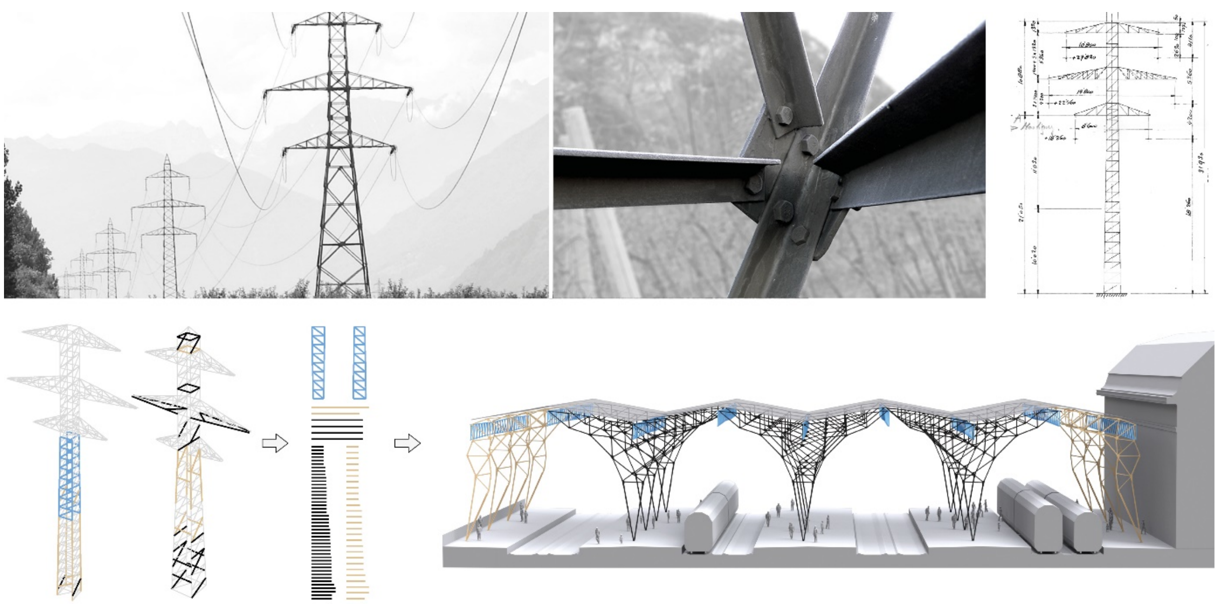

Figure 12. Schematic view of a train station roof truss made of electric pylon parts, after layout optimization[38]. Top row images courtesy of Swissgrid.

The same computational basis can be extended in order to synthetize a common stock of bespoke elements that can be assembled into diverse structures of same or different typologies[39,40]. The approach results in kit-of-parts elements that are generally oversized compared to one-off minimum weight solutions. However, producing only a subset of all system members and reusing them multiple times reduces environmental impacts significantly[40].

Construction detailing: allowing the unforeseeable reassembly

Reconsidering contemporary construction techniques in light of durability, versatility, reversibility, modularity, and transformability, it is currently accepted that (1) long-term durability is sufficiently controlled and ensured by building codes and that (2) versatility has become common in design briefs. However, reversibility (3) is rarely achieved and current modular (4) and transformable (5) constructions only allow reuse in a narrow, close-ended range of applications.

Reversible connections are less common today than in the past. In ancient Eastern and Western timber constructions, prefabricated structural elements are joined by interlocking geometries and with simple pegs. During industrialisation, assembled steel structures, whether wedged, pegged or bolted, would almost always also be demountable. Yet the ability to be demountable was rarely a design objective in itself. The design of the Crystal Palace is an early exception[41]. Its columns and beams originally assembled in Hyde Park were re-erected in Sydenham in a modified layout and with new additions[42].

Today, the reuse of steel structures is easier than for other materials because they are usually dismountable through reversible connections. Their components, which usually have standard cross sections and grades, can be cut and reshaped. In addition, the capacity of steel elements can be assessed through visual, acoustic or load testing. This might be similarly possible for timber elements but less easy to achieve in the case of concrete elements. The availability of *material passports* documenting the composition of structural elements will potentially ease their future reuse.

A number of technical solutions have recently been developed to improve the reversibility of reinforced concrete systems[43,44]. In particular, commercial solutions are available to bolt together steel connectors that are anchored into prefabricated concrete elements (e.g. www.peikko.com or www.anstar.fi). Each reassembly involves the localized destruction and replacement of the grout used to protect the steel connection from corrosion and fire. Research has also been carried out to connect steel beams and concrete decks via novel, bolted shear connectors[45]. Future advancements in the field may involve connections allowing the replacement of an element, e.g. a column, without dismantling the parts connected to it, e.g. the floors above and below.

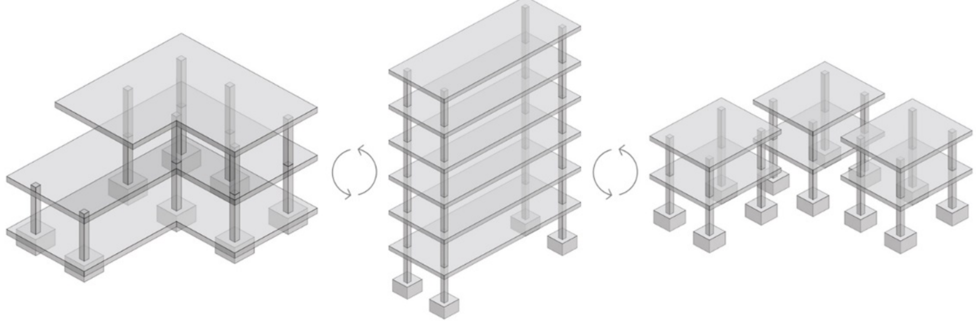

Figure 13. The non-destructive ever-reshaping of a structural system as a vision.

Not only must structural components be designed with reversible connections in order to be effectively reused, their geometry and structural capacities must also allow their reassembly into a wide, open-ended set of unforeseen structural layouts, Figure 13. In this context, subsequent structural systems must be envisaged as unforeseeable because functional requirements for buildings evolve much faster than the expected life-span of structural components. For instance, dwelling and work have considerably evolved over the last centuries and are expected to keep changing: the family unit has shrunk or is being replaced by other types of communities; new disrupting appliances have led to new spaces (e.g. the underground parking garage, the television room, the equipped kitchen, the larger bathroom); new theories have transformed office rooms into open spaces; the distinction between home and workplace is softening. In urban areas, political pressures may push a series of office buildings to become apartment buildings, or vice versa. The non-destructive adaptation of a building therefore includes the change of floor-to-floor height, the reshaping of floor outline, the rearrangement of column and wall layouts, the increase of applied loads, the creation or deletion of vertical shafts, the resizing of circulation cores, and the adaptation to upgraded mechanical, electric, plumbing and data networks.

All this actually follows a shift of perception. The structural skeleton is not seen as the immutable artefact in the building anymore. It is seen as a transient assembly of components that is potentially transformable for future needs, similarly to building toys being reassembled every day to create new unexpected stories.

In addition, open-ended rearrangements of structural systems are expected to allow architectural differentiation and avoid monotony, which is customary of modular structures. Previous attempts to address this challenge have failed to break into mass production market. Yet, the way load-bearing systems in steel or reinforced concrete are created today is fairly similar for the vast majority of non-institutional buildings (e.g. office and industrial buildings, housing, schools), even though their architectural character may differ substantially. In other words, the prospect of a transformable load-bearing system that supports diverse architectural influences over time is not necessarily contradictory.

Environmental assessment: new metrics.

Currently available metrics to assess or compare the sustainability of products or whole buildings are produced by Life-Cycle Assessments (LCA). Briefly, LCA computes the life-cycle impacts (e.g. in terms of equivalent $CO2$) of a certain functional unit (e.g. a bridge, a building, a slab, a staircase) within a certain study boundary (e.g. cradle-to-cradle, cradle-to-gate). The integration of reused or reusable products disturbs the conventional assessment in various ways.

First, the assessment must consider all past and future use-cycles of the reusable product. If the number and duration of those use-cycles is unknown, the added detrimental impact necessary to make a product reusable is assigned to the initial manufacturer instead of being distributed among all future re-users. Such assessment goes against the design of reusable parts. On the contrary, if a portion of the initial manufacturing impacts is assigned to a re-user, those impacts might be more detrimental than a more efficient recently-manufactured product with similar functional unit. Such assessment goes in favour of the production of new products. Both scenarios happen because LCA is about quantifying the environmental impacts of a production, whereas reuse is more about avoiding the need for future productions. For instance, to the question “is a short-lived building better than a long-lasting building?”, the answer does not matter anymore as long as building parts are reusable.

Second, in order to compare two LCAs of reusable products, it is required that their functional unit are equivalent, hence both products must have the same reuse potential. As of today, there is a lack of measures of reusability of a product or its parts. For instance, reusability depends on versatility (e.g. what functions could a product be reused for?), connectivity (e.g. how many different configurations could product parts be reused in?), utilization (e.g. will a product be oversized? What is the ratio between its actual use and its full potential?), external demand (e.g. will there be need for such a product in the future?), and surrounding context (e.g. to what extent will external systems remain compatible with the product?). All those features are currently hard to quantify: they do not have any unit of measure, and the necessary data to back up probabilistic predictions is non-existent.

Third, rather than comparing LCAs of products with similar functional units, what would be useful for a designer is to compare different functional units together, or in other words, to compare different reuse strategies together. Again, both quantification metrics and relevant benchmarks are currently missing. Being able to compare the potential for reusability of a product together with the functional unit of its actual reuse is also a prerequisite to avoid down-cycling reuse. Down-cycling reuse happens when a reused product is oversized or over-efficient for its new purpose, meaning that its reuse elsewhere, for another purpose, would have avoided the manufacture of a more demanding product.

In summary, the value of a reused or reusable product is more related to what it potentially or effectively replaces than to the environmental impacts of its own manufacture and use. Reuse requires even more nuanced interpretations of LCA results and the notion of reusability still lacks proper metrics and benchmarks. Not only do structural designers need those metrics to improve their design, but their input is also needed to define them.

Conclusion

In light of a circular industrial economy, the current mainstream structural design practice is senseless because it produces load-bearing systems whose obsolescence leads to the premature demolition of all parts. In response, component reuse avoids resource use and new manufacturing by reclaiming components from old systems and rearranging them in new structures. The reuse strategy was more common in the past than today but a resurgence is within reach. It will be accompanied by paradigmatic shifts related to material procurement, design methods, construction detailing, and footprint assessment. Designers are in a unique position to lead this new transition.

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