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Design of Load-Bearing Systems for Open-Ended Downstream Reuse

Corentin Fivet

Structural Xploration Lab, EPFL, Switzerland

corentin.fivet@epfl.ch

Abstract. This paper discusses the design of load-bearing systems for buildings with regard to their current lack of open-ended reusability. The reason for dismantling load-bearing systems today tends to be less related to material degradation than to a loss of functional fit with an evolving building program. It can therefore be expected that load-bearing components are reused in other systems, which extends their service life and avoids the manufacture of other components. Common design strategies to ensure the actual reusability of components consist in guaranteeing that the assembly is durable, versatile, modular, reversible, and adaptable. This paper (a) reviews these features, (b) illustrates by means of case studies that, without minimum threshold, they do not guarantee the repurpose of components into different, unforeseen systems, and (c) describes opportunities and challenges related to the design of more open-ended sets of load-bearing elements, i.e. sets whose element types allow for a substantially large number of diverse assemblies, in terms of floor plans, spans, loads, support layouts, connection types, architectural language, and integration with other building systems.

Keywords: load-bearing system, reuse, design-for-disassembly, circular economy

1. Introduction

The design of load-bearing systems – i.e. systems of slabs, walls, beams, and columns – rarely aims at producing reusable parts. They are commonly assumed to be the building systems with the longest service life. In some designers' mind, they are even meant to last forever. However, the demolition of load-bearing systems happens at a non-negligible rate, especially in areas subject to high land-value pressures. As living needs and working cultures constantly evolve, buildings, sooner or later, are declared unfit for rational use. First attempts replace or refurbish the fit-out. Next attempts operate on the envelope. Eventually, load-bearing systems are declared obsolete because support layouts, load-carrying capacities, or ceiling heights do not meet new functional requirements. Scheduled to last for several decades, load-bearing systems may consequently be dismantled way before their expected end of life [1]. Still, if properly designed, their components could remain safe and useful for a substantially longer service life.

The disposal of load-bearing components is a disaster for embodied carbon and solid waste generation [2][3][4][5], mainly because of their proportionally high volume, high mass, and energy-intensive manufacturing processes. Reusing load-bearing components over multiple building life cycles is therefore a promising path to respond to the environmental challenges faced by the construction sector [6].

Unlike recycling, component reuse aims at avoiding material reprocessing while making the best use of existing component features, e.g. dimensions, strength, stiffness, connectivity, fire/water/shock resistance. The reuse of load-bearing components may involve their relocation, their repurpose, and/or the modification of their utilization rate, i.e. their actual performance value over their maximum allowable performance value.

Although load-bearing systems are rarely designed to be reused, pre- and post-industrial construction history includes several buildings that are constructed with reclaimed load-bearing material [7][8][9][10][11][12]. These success stories are generally reliant upon fortunate stock availability, i.e. fortuitous timing, location, and matching features. In order to achieve circular economy at scale, however, a proper and systematic design of load-bearing elements for reuse is required [13][14]. There are numerous challenges related to the reuse of structural components [15][16], this paper focuses on conceptual design considerations.

Section 2 of this paper is a review of the qualities that should be attributed to reusable building components. Section 3 is a critique of the effectiveness of reuse through the study of two 50-year-old buildings that were originally designed for reassembly. Section 4 introduces open-endedness as a necessary requirement for effective reusability of load-bearing assemblies. Related opportunities and challenges are discussed in the same section. The last section concludes that research is needed to obtain benchmarks on open-ended reusability and to develop new construction technology allowing the effective, unforeseen reuse of load-bearing components.

2. State-of-the-art strategies to ensure reuse

Special attention is required when designing products in order to ensure their reusability once the system to which they belong reaches its end of life. Various authors have provided lists of requirements [1][17]. The following subsections recompile five necessary features for reusable assemblies: durability, versatility, modularity, reversibility, and adaptability. They concern all scales: the system, the components, and the connections between parts.

2.1. Durability

Durable assemblies ensure the maintenance of functional and technical characteristics of materials throughout (and beyond) their service life. Design considerations include the protection of the components against damage, before, during, and after service. Also, it is expected for instance that mechanical properties remain sufficiently good (i.e. useful) despite long-term creep or other material degradation due to cyclic or rare loading.

2.2. Versatility

Versatile assemblies are capable of supporting other functions and services without being transformed. For instance, it means that functional zones are independent of the support layout [18]; that a column-and-beam building system is a good fit for both office or residential purpose; that a load-bearing system does not present thermal bridges when insulation is added to the envelope; or that foundation blocks can withstand new loads. Versatility constitutes one dimension of the 'Open Building' concept [19][20]. Recent applications are mentioned in [21][22][23][24].

2.3. Modularity

Modular assemblies are made of elements of similar type that can be placed interchangeably at different locations. Modularity facilitates the integration of components in the system. In this respect, it is connected to standardization. A modular system might not be reversible (e.g. cemented wall of regular bricks) and a reversible system might not be modular (e.g. dry wall of irregular stones).

2.4. Reversibility

Reversible assemblies can be undone into any previous state, with no or negligible damage. Guidelines for *design for disassembly* [25][26] or *design for deconstruction* [27] can be found in [1][28][29]. Reversibility places the focus on connections, e.g. mechanical fasteners, interlocking arrangements, or simple face-to-face contact. Although bolted steel or timber systems are most commonly used, reversible connections also exist for reinforced concrete systems [30][31][32].

2.5. Adaptability

Adaptable assemblies allow some of their parts to be removed, added or rearranged in order to meet new spatial, functional, or technical requirements. *Transformability*, *extensibility*, *reducibility* and *variability* can be seen as special cases of adaptability. Transformability is achieved if the assembly can have completely new spatial, functional, and technical features after rearrangement. Extensibility and reducibility are specific to assemblies in or from which some parts can be added or removed, respectively. Variability is specific to assemblies whose parts (members or connections) have variable states, e.g. columns with adjustable height, or slidable slab-to-column connections [33]. A system that is adaptable might not be reversible – e.g. non-reversible connections used for adding an overhanging balcony to a building –, and one that is reversible might not be adaptable – e.g. the removal of a block from a dry stone arch would jeopardize the structural integrity of the system.

3. Case studies

The following case studies show that the five abovementioned requirements can be satisfied without ensuring reusability. The two buildings considered are designed by Swiss architect Jakob Zweifel (1921-2010). Their load-bearing system was designed for reassembly, which originated more from the need for versatility than from environmental concerns. Fifty years later, they constitute first-hand examples to study shifts of functional and technical requirements that happen over long periods. Originally designed for reuse, they are effectively able of disassembly and reassembly, but they are not fully able of repurpose.

3.1. Case Study: Agro Research Centre, St-Aubin, Switzerland, 1965-69

The Agro Research Centre in St-Aubin (Canton of Fribourg, Switzerland) is a campus of several buildings using the same reversible reinforced-concrete system [34][35], figure 1. The heterogeneous program called for a highly diverse set of spatial features: administrative offices, various laboratories, greenhouses, experimental livestock sheds, a mill, a farm, and a slaughterhouse. In addition, high functional adaptability over time, i.e. an ability to grow and redistribute functional zones, was required in order to adjust to evolving research needs. The developed campus combines high rationalization with prefabrication. It consists in a carpet-like layout of one-story-high buildings with continuous skylights. The skylights are created in between prefabricated reinforced-concrete (PRC) u-shaped shells. Extrusions of the shells are interlocked within PRC transverse beams, which are supported by PRC columns of various heights. Columns are driven into PRC foundation blocks. A quick description shows that the system shares minimum features of reusability:

- *durability* – although the initial construction was lacking proper protection against rain and snow cycles, the assembly was made durable after subsequent waterproofing;
- *versatility* – the highly diverse program fitted for almost 50 years;
- *modularity* – all u-shape shells have the same width, all beam lengths are multiple of the width of u-shape shells, and columns could be placed under any beam.
- *reversibility* – thanks to the low height of the building, only pure compression contact is needed between the u-shape shells, beams, and columns; ensuring full reversibility of the system; the contact between two concrete elements is performed by a small, replaceable rubber pad;

- *adaptability* – over the service life of the campus, extensions using the same construction system have been created, and entire buildings have been moved; in addition, beams and u-shape shells of different lengths can be combined to achieve various spans, which means that each building can be freely extended in both directions.

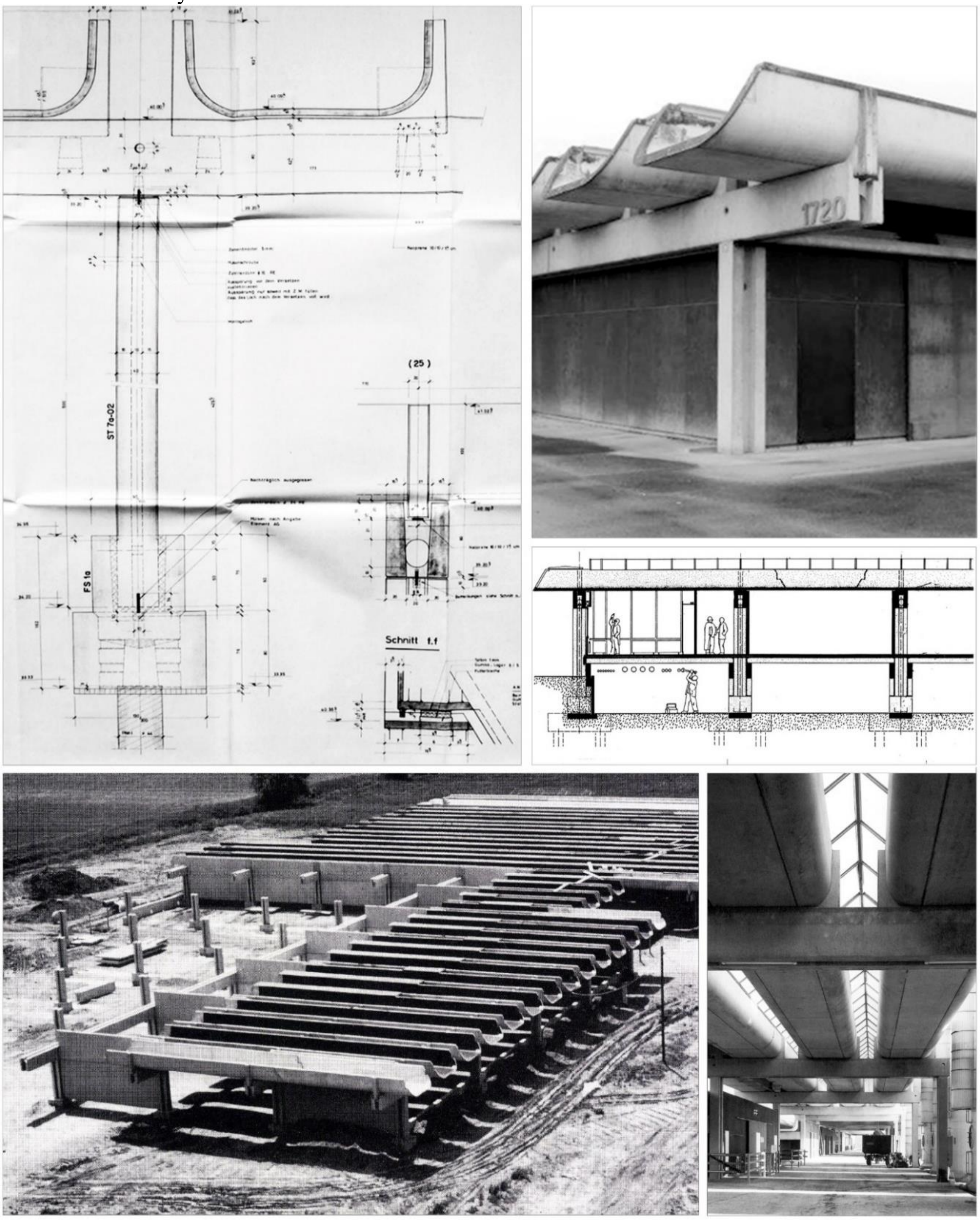

Figure 1. Agricultural Research Centre, St-Aubin, Switzerland (adapted from [34] and [35]).

The building is unoccupied since the departure of the last tenant at the end of 2016. Besides on-site refurbishment and complete demolition, the reuse of the building components in new locations and for new purposes is one of the options on the table for the current owners of the complex. Students at EPFL

(Fröhlich Studio) have spent a semester exploring potential reuse contexts. Still, the brutalist nature of the system hardly matches new building energy standards; the overdetermined nature of the system does not allow reconstruction over multiple stories; and the architectural language of the u-shaped shells is stranger to current practice. Hence, the actual reuse potential of the system remains very limited.

3.2. Case Study: EPFL Campus, Ecublens, Switzerland, 1970-1982

The next case study is the first development of the campus of the *Ecole Polytechnique Fédérale de Lausanne* in Ecublens (Canton of Vaud, Switzerland) [35]. The initial design took into account possible changes in the type of teaching, research, and population. It resulted in an integrated, differentiated structure of interconnected 2- to 3-story-high buildings. A raised circulation floor separates car and pedestrian traffics. A roof structure covers all external circulations on the top floor.

Figure 2. EPFL Campus, Ecublens, Switzerland (adapted from [35]).

Again, the roof structure satisfies all reusability criteria up to a certain degree:

- *durability* – the structural system is well-protected from degradation;
- *versatility* – the large span between columns does not constrain the covered area partitioning;

- *modularity* – the same square grid runs throughout the roof structure;
- *reversibility* – steel assemblies are bolted, hence fully dismountable;
- *adaptability* – the span between columns supporting the steel grid can be varied.

Despite these significant qualities, the end-of-life reuse of the load-bearing system is far from being secured, mainly due to its (outdated) visual expression and to its inability to withstand significantly new load distributions or changes in ceiling heights.

4. Open-ended reusability: designing for the unknown

Both case studies present all traits listed in section 2. However, the extent to which they implement those traits is too small for effective reusability after fifty years. In other words, the design of the components is so specific to the initial system that they can hardly generate other assemblies. They cannot meet new, initially unforeseen spatial, functional, and technical requirements.

The same remarks can be established for almost all load-bearing systems currently in use in buildings. For instance, standard reversible steel, timber, or reinforced concrete construction systems, unless being combined with large stocks of diverse elements, do not allow for rearrangements with other ceiling heights or support spans.

Because next life cycle requirements are unknown at the time of design, components, connections, and assemblies should instead be such that they allow large sets of diverse rearrangements – i.e. durability, versatility, modularity, reversibility, and adaptability must be open-ended.

Concretely, open-ended rearrangements of load-bearing components would mean, by and large, that:

- the span between two supports is not constrained by the length of beams or slab elements, which for instance could be achieved through sliding connections or densely distributed connection points;
- the load-bearing capacity of an arrangement of beams, slabs, or columns ranges beyond what is provided by the components alone; in other words, the strength and stiffness of the arrangement can be tailored irrespectively of span and elements type;
- floor outlines, ceiling heights, support layouts, vertical service duct locations, and the envelope can be shaped up to large extents irrespectively of constraints set by load-bearing elements;
- same connection details can transfer multiple types of forces indifferently;
- the load-bearing system allows as much integration as possible with other building systems;
- the architectural language of a building can be altered with little to no impact on its load-bearing elements.

On the one hand, achieving open-ended reusability implies that each component is more likely to be reused soon. Interesting savings in storage, labour, and remanufacturing costs can therefore be expected. On the other hand, open-ended reusability must be balanced with material efficiency and resilience in order to control structural oversizing and unavoidable damage.

In theory, complete open-ended reusability is not achievable because the set of all possible spatial, functional, and technical requirements is infinite and continually evolving. We can assume that how people will live and work in the next century or so is unknown at the time of design. However, to increase the open-ended reusability of load-bearing systems in practice remains an environmental necessity. This need calls for new research and development directions.

First, what constitutes open-ended reuse must be further characterized, to a point where two solutions can be compared with sufficiently high precision and confidence. Building on real case studies, best solutions of open-ended reusability could be identified and used as benchmarks. Building on large, simulated data sets, statistical relationships between stocks of components and available (re-)arrangements could lead to new design principles for ensured reusability.

Second, new construction techniques allowing for open-ended rearrangements must be developed, while controlling environmental impacts, economic costs, and social values. Taken as a new performance criterion, open-ended reusability is an opportunity for innovation and a trigger for shifting conventional design paradigms towards more *design for the unknown*.

5. Conclusion

As load-bearing systems are mostly abandoned because of functional obsolescence, it is crucial that rearrangements of their components allow for new spatial, functional, and technical requirements. Through a redefinition of associated terms and two case studies, this paper has shown that current best practices to design reusable load-bearing components – i.e. ensuring durability, versatility, modularity, reversibility, and adaptability of the assembly – are not satisfying. We suggest that the design of reusable load-bearing components become considerably more open-ended than what is currently accepted. Calling for research on stock characterization and calling for new construction techniques, the explicit design for open-ended reusability could give confidence that unforeseen reusability will actually happen right after loss of usability, which would reduce storage and production needs, i.e. some of the critical environmental impacts of the construction industry.

6. References

[1] Durmisevic E 2006 Transformable building structures - Design for disassembly as a way to introduce sustainable engineering to building design & construction (TU Delft)

[2] Sartori I and Hestnes 2007 A Energy use in the life cycle of conventional and low-energy buildings: A review article *Energy and Buildings* (*Elsevier* vol 39) pp 249–257

[3] Kaethner S and Burridge J 2012 Embodied CO2 of structural frames *The Structural Engineer* (The Institution of Structural Engineers) pp 33-40

[4] Webster M D, Meryman H, Slivers A, Rodriguez-Nikl T, Lemay L and Simonen K 2012 Structure and Carbon - How Materials Affect the Climate. *SEI Sustainability Committee, Carbon Working Group* (Reston, VA: American Society of Civil Engineers ASCE).

[5] De Wolf C, Ochsendorf J, Cox D, Hattan A, Yang F and Charlson A 2015 Survey of material quantities and embodied carbon in existing building structures *ICE Journal of Engineering Sustainability*.

[6] De Wolf C, Brütting J and Fivet C 2018 Embodied Carbon Benefits of Reusing Structural Components in the Built Environment: a Medium-rise Office Building Case Study *PLEA Conference* (Hong-Kong).

[7] CE100 Network 2016 Circularity in the Built Environment, Case Studies (Ellen McArthur Foundation)

[8] Chopin J and Delon N 2014 *Matières Grises* (Paris : Éditions du Pavillon de l'Arsenal)

[9] Ghyoot M, Devlieger L, Billiet L and Warnier A 2018 *Déconstruction et réemploi, comment faire circuler les éléments de construction* (Presses polytechniques et universitaires romandes)

[10] Gorgolewski M 2018 Resource Salvation, The Architecture of Reuse (Wiley Blackwell)

[11] Falk B and Guy B 2007 Unbuilding: Salvaging the Architectural Treasures of Unwanted (Taunton Press)

[12] Addis B 2006 Building with reclaimed components and materials (London: Earthscan)

[13] Cheshire D 2016 Building Revolutions, Applying the Circular Economy to the Built Environment (RIBA Publishing)

[14] Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions 2015 *Closing the loop - An EU action plan for the Circular Economy* (Brussels: European Commission)

[15] Iacovidou E Purnell P 2016 Mining the physical infrastructure: Opportunities, barriers and interventions in promoting structural components reuse *Science of the Total Environment* 557-558 (Elsevier) pp 791-807

[16] Tingley D D, Cooper S and Cullen J 2017 Understanding and overcoming the barriers to structural steel reuse, a UK perspective *Journal of Cleaner Production* (Elsevier vol 148) pp 642-652

[17] Allwood J M and Cullen J M 2012 *Sustainable materials - with both eyes open* (Cambridge: UIT Cambridge)

[18] Habraken N J, Boekholt J T, Thijssen A P and Dinjens P J M 1976 *Variations: the systematic design of supports* (Cambridge: MIT Press)

[19] Habraken N J 2003 Open Building as a condition for industrial construction ISARC2003 : the future site : proceedings of the 20th international symposium on automation and robotics in construction (Eindhoven)
[20] Kendall S 2017 Four Decades of Open Building Implementation: Realising Individual Agency in Architectural Infrastructures Designed to Last *AD Architectural Design Special Issue: Loose-Fit Architecture: Designing Buildings for Change* Issue 5 (vol 87)
[21] Kendall S and Teicher J 2000 *Residential Open Building* (London & New York: E & FN Spon)
[22] Leupen B, Heijne R and van Zwol J 2005 *Time-Based Architecture* (010 Publishers)
[23] Till J and Schneider T 2007 *Flexible Housing* (Routledge)
[24] Wong L 2017 Adaptive Reuse – Extending the Lives of Buildings (Basel: Birkhäuser)
[25] Boothroyd G and Alting L 1992 Design for assembly and disassembly *CIRP Annals-Manufacturing Technology* 41(2) pp 625-636
[26] Kriwet A, Zussman E and Seliger G 1995 Systematic integration of design-for-recycling into product design *International Journal of Production Economics* 1 (volume 38) pp 15-22
[27] Crowther P 2004 Design for disassembly to recover embodied energy *The 16th International Conference on Passive and Low Energy Architecture* (Melbourne)
[28] Addis B and Shouten J 2004 Design for deconstruction - Principles of design to facilitate reuse and recycling (London: CIRIA)
[29] Paduart A, Debacker W, Henrotay C, Asnong K, De Wilde W and Hendrickx H 2008 Technical detailing principles for the design of adaptable and reusable construction elements in temporary dwellings *1st Conf. on Design and Nature* (vol 109) pp 425-433
[30] CD20 Building Systems https://www.cd20.nl/en/systems/CD20BuildingSystem.php
[31] Paananen T and Suur-Askola P 2018 Peikko and the circular economy, practical considerations (Peikko)
[32] Réseau CTI 2012 Nouveaux systèmes constructifs Démontables en Rénovation ou déconstruction pour valorisation et recyclage simplifiés et attractifs des produits et matériaux, Projet DEMODULOR · Synthèse non confidentielle (Agence de l'Environnement et de la Maîtrise de l'Énergie (ADEME)
[33] Wang L, Brown C, Webster M, Hajjar J 2015 Experimental Investigation of Deconstructable Steel-Concrete Shear Connections in Sustainable Composite Beams *Proceedings of the ASCE/SEI Structures Congress 2015*, Portland, Oregon, April 23-25
[34] Zweifel J 1969 Centre de Recherches Agricoles in St. Aubin (Fribourg) *Bauen + Wohnen International Zeitschrift* 23
[35] Zweifel J 1996 Jakob Zweifel Architekt, Schweizer Moderne der zweiten Generation (Zürich: Verlag Lars Müller)

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