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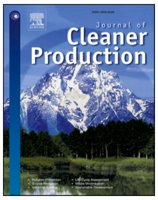

Reuse of cut concrete slabs in new buildings for circular ultra-low-carbon floor designs

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ABSTRACT

The study explores an original idea that responds to the urgent need to reduce the detrimental environmental impacts of load-bearing floor construction in new buildings by reusing saw-cut reinforced concrete (RC) pieces salvaged from soon-to-be demolished structures. Cutting and reusing large RC pieces rather than crushing them to rubble is an untapped emerging circular construction method with a high potential for reducing waste generation, natural resource consumption, and upfront greenhouse gas emissions. Through an iterative design and analytical process, the study demonstrates how discarded cast-in-place RC floors can be cut and reused to build new low-carbon, little-extractive, load-bearing building floors. The study provides two new floor design solutions that valorise frequently discarded construction components (reinforced concrete slabs and steel profiles), combining construction technologies already used by the industry. The parametric design of 20′280 combinations of donor and receiver structures and their environmental analysis through Life-Cycle Assessment show that the new floor systems have shallow detrimental environmental impacts, with a reduction of upfront greenhouse gas emissions averaging 80 % compared to conventional practice. Floor-system solutions as low as 5 $\mathrm{kgCO_2e/m^2}$ have been obtained. Structural assessments additionally show that flat slabs that are currently demolished meet the structural requirements at the preliminary design stage for reuse in new office or housing buildings. In particular, thanks to mandatory minimum reinforcement, 18-cm thick or thicker flat slabs built in Switzerland after 1956 and spanning up to 4 m are expected to be technically reusable as-is over their entire span. Overall, this study sets up a new benchmark for innovative floor systems with minimum environmental impacts and calls for considering soon-to-be demolished RC structures as mines of valuable construction components.

1. Introduction

1.1. Background

1.1.1. Low-carbon load-bearing floor design

Construction and demolition activities emit about 11 % of energy- and process-related greenhouse gas emissions worldwide (IEA, 2019). To lower the environmental burdens imposed by this sector, reducing the global warming potential of load-bearing structures remains a top priority because of their high-mass and high-emission manufacturing processes (Foraboschi et al., 2014; Orr et al., 2019; Trigaux et al., 2021). Up to 45 % of embodied carbon in buildings is indeed due to the construction of the structure, with floors usually being the most significant contributors in multi-story buildings (Sansom and Pope, 2012; Foraboschi et al., 2014; Stephan and Athanassiadis, 2017; Gauch et al., 2023). Today, new floor slabs in multi-story buildings are mostly built of reinforced concrete (RC), as its high tensile resistance confers compactness to the slabs at minimum costs. In addition, RC slabs are appreciated for their good fire-resisting, thermal, and soundproofing properties.

Concrete – a material made of cement and water that bind aggregates and sand - is the most used construction material, with a 14 billion-$\mathrm{m^3}$ yearly global production (Global Cement and Concrete Association, 2023). Steel bars are embedded in concrete to form structural RC elements capable of bending resistance. Cement production alone causes about 5–9 % of global $\mathrm{CO_2}$ emissions (Shen et al., 2015; Miller et al., 2016, 2018b), and its consumption is expected to rise by 12–23 % by 2050 compared to 2018 (IEA and CSI, 2018). The concrete and cement

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industry is the source of other detrimental impacts: regional material scarcity is precipitated by the large concrete demand (Habert et al., 2010; Ioannidou et al., 2017); the local availability of sand is a source of major political, ecological, and economic conflicts (Torres et al., 2017); water supply is locally problematical since 75 % of it is consumed in areas already experiencing hydraulic stresses (Miller et al., 2018a); concrete manufacturing releases air pollutants that are harmful to human health (Miller and Moore, 2020).

Reducing material quantity through more efficient design is one of the design strategies to decrease embodied carbon in newly-produced floors (Shanks et al., 2019; Jayasinghe et al., 2022a, 2022b). This strategy was already investigated in the early days of RC when materials were a significant expense. Pioneering engineers like Hennebique and Nervi developed ribbed slabs of minimum material quantity by locating material only where structurally needed (Addis, 2007; Halpern et al., 2013). However, this approach was rapidly superseded by less labour-intensive and more resource-intensive methods, prioritising regular reinforcement patterns and flat slabs to speed up construction and reduce the risk of errors. A cultural change would be needed to generalise optimum building slabs again (Orr et al., 2019; Shanks et al., 2019). Recent research nonetheless explored new slab systems that use less material than conventional ones (Liew et al., 2017; Hawkins et al., 2020; Ismail and Mueller, 2021; Ranaudo et al., 2021; Whiteley et al., 2023).

Another strategy is to reduce the environmental impact of cement production itself, usually by focusing on clinker manufacturing (Habert et al., 2020). Alternatives to regular Portland cement clinker have attracted much research interest (Sivakrishna et al., 2020; Li et al., 2022). Limestone calcined clay cement (LC3) is one of the most promising alternatives (Scrivener et al., 2018) because of the wide availability of its input materials and because it reduces the CO_2 emissions of cement production by up to 30 % (Antoni et al., 2012; Berriel et al., 2016). However, its performance at the structural level remains unknown (Sharma et al., 2021), and other externalities of concrete, such as stresses on regional sand or water reserves, remain unaddressed.

Not only are efforts needed to reduce the detrimental impacts of concrete production and increasing demand, but existing resource management must also improve. Concrete waste represents 30 % of the total solid waste in Europe (Böhmer et al., 2008), and discarded quantities are expected to increase within the coming decades (Wüest and Partner, 2015; Arehart et al., 2022). When demolition is unavoidable, an option to limit waste accumulation is by producing so-called "recycled" concrete mixes, where natural aggregate is partially replaced by aggregate crushed from demolition concrete (Wang et al., 2021). Nevertheless, similar or higher cement content is needed to produce "recycled" concrete, resulting in similar to higher CO_2 emissions (Marinković et al., 2010; Xing et al., 2022). Additionally, Silva and de Brito (2020) claim that the lower mechanical properties of "recycled" concrete imply a larger material consumption, which reduces the positive impacts of recycling.

As highlighted by Thomsen and Andeweg-Van Battum (2004), Abramson (2016), and Salama (2017), demolitions of concrete structures are often caused by socioeconomic factors unrelated to physical condition, meaning that the crushing and downcycling of reinforced concrete imposed by conventional waste streams occurs prematurely and that structural capacities of the RC could be used longer. One option to use them longer is by carefully extracting large RC pieces from soon-to-be demolished structures and reusing them, with minimum alteration, as structural components in new structures (Addis, 2006a; Küpfer et al., 2023).

Reusing components to build structural floors is not a common practice and is even rarer in multi-story buildings. An iconic historical example from the 19th century is the Crystal Palace, of which the floor structure made of trussed iron girders, wood beams, and planks, was disassembled and reassembled in a new location (Addis, 2006b; Stricker et al., 2021). Timber has been reused since always in construction, and recent single-family house relocations have illustrated complete old timber floor reuse (Gorgolewski, 2017; Stricker et al., 2021). Over the past decades, multi-story building floors have reused steel girders, like the K118 building in Winterthur, Switzerland, but to comply with sound and fire requirements, they were combined with new RC decks (Stricker et al., 2021). Taking advantage of the sound- and fire-resistance of RC, the remainder of this article focuses on the reuse of cast-in-place RC pieces to build new load-bearing floors in order to value at best the large quantities of discarded RC while reducing raw material dependency and production-related greenhouse gas emissions.

1.1.2. *Concrete reuse*

Concrete reuse is an untapped design approach, where RC pieces are carefully extracted from donor buildings, generally using circular saws and lifting equipment (Fig. 1), and reassembled in a new structure after no or minor alteration. Küpfer et al. (2023) documented over 50 building structures reusing concrete structural elements built between 1967 and 2022 in Europe and the United States. The literature reports environmental gains on resource use, CO_2 emissions, waste generation, and economically beneficial experiences (Küpfer et al., 2023). Nonetheless, reusing RC pieces in new structures remains rare today. The transitional barriers to more widespread implementation of reusing concrete are mostly economic inertia that favours demolition routines over more delicate deconstruction processes, the lack of market-proven liability schemes, and the small set of design options, in particular, to reuse pieces cut from cast-in-place concrete structures. This article aims to address this last point.

Most documented built precedents reusing RC reclaim precast elements, like wall and slab panels (Mettke, 1995; Heyn et al., 2008; Huuhka et al., 2019; Stenberg et al., 2022). In contrast, few projects have reused cut RC from cast-in-place (CIP) structures (Küpfer et al., 2023). The reason behind this contrast partly resides in that deciding where to cut RC pieces in a CIP structure is not trivial and that cutting implies a change in the static system unless new embedded connections are built (Widmer et al., 2023). Nevertheless, CIP remains a predominant type of RC structure in several territories, including Switzerland, and its reuse should be further explored, including for building new floor systems.

Current ways to reuse RC pieces cut from CIP structures are confined to two main design approaches (Küpfer et al., 2023). The first one reuses flat blocks that primarily work in compression in the new design. Recent parking pavements (Küpfer et al., 2022) and a 10-m spanning arch footbridge (Devènes et al., 2022) illustrate this approach. The second approach reuses large structural assemblies that comprise horizontal and vertical parts and conserves existing connections. This approach has been used to build 2-story high buildings (Superlocal, n.d.) and another under-construction one-story high pavilion (Claessens-Vallet, 2023). This approach globally allows reusing most RC structural characteristics, including the bending resistance provided by the tensile capacity of the steel reinforcement bars. Still, it imposes significant constraints on the new design layouts. In addition, specific lifting and transportation equipment are generally required.

This study investigates another approach: reusing long flat pieces cut from CIP RC into new structural systems that re-utilise their bending capacities. This alternative approach is a proposition to simultaneously take advantage of all existing structural characteristics of RC slabs while avoiding the drawbacks of assembly reuse. To the authors' knowledge, reusing long, flat pieces of cut CIP RC in bending to build new floor systems is an untapped circular design strategy. A similar approach was only used conceptually by Widmer et al. (2023) when developing an algorithm to allocate CIP RC pieces from and to given floor plans, relying on strengthening the pieces and reconstructing fixed-end connections. This variant, however, implies additional construction phases, techniques, and costs. On the contrary, this study does not consider the addition of strengthening or the reconstruction of fixed-end connections.

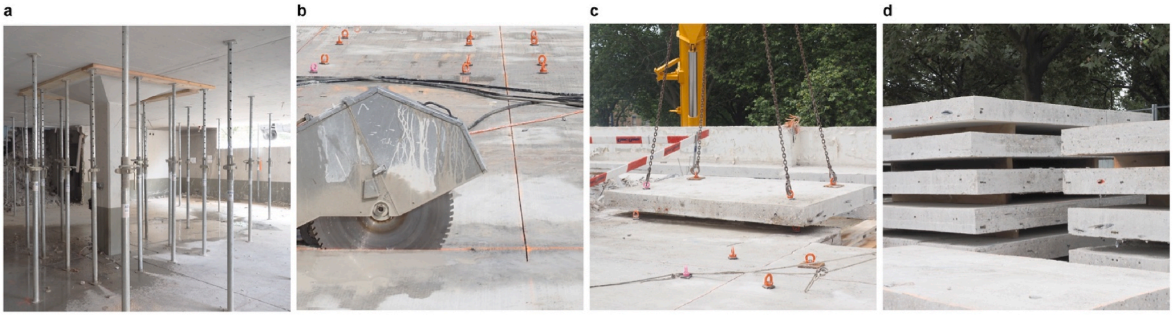


Fig. 1. Processes to extract concrete for reuse, in chronological order: (a) shoring of the obsolete structure, (b) piece cutting, (c) lifting, and (d) storage.

1.2. *Objectives and significance*

The study explores an original and disruptive idea that combines the urgent need for low-carbon load-bearing floors and more efficient material use with the emerging strategy of reusing discarded CIP RC as pieces. By developing and assessing new floor systems, the study aims to demonstrate how discarded RC floors can be cut and reused as-is to build new building floors and evaluate the associated environmental impacts. The specific goals of this study are threefold:

1. To investigate the design potential of reusing CIP RC elements to build low-carbon floor systems and provide a procedure to define the allowable dimensions of the CIP RC to reuse them as they are;
2. To develop construction systems that valorise as much as possible the structural properties of discarded RC and support efficient material reuse;
3. To benchmark the environmental impacts of the new systems and understand the influence of selected donor or receiver parameters on the design and environmental footprint.

The study provides two new floor design solutions that valorise discarded materials (RC and steel) widely and rely on construction technologies already used in the industry. The new floor systems bring unprecedented environmental benefits, with a reduction of upfront greenhouse gas emissions averaging 80 % and solutions as low as 5 $kgCO_2e/m^2$. Potential areas of implementation of the new systems include all industrial basins where cast-in-place RC structures are commonly demolished. Switzerland, the authors' home country, falls in this category and is chosen as a normative and technological context for this study.

The study is organised as follows. The scope and methodology of the study are presented in Section 2. Section 3.1 details the new floor systems and introduces the procedure to estimate the allowable span of the cut RC pieces for reuse. Section 3.2 presents the results of the parametric design and environmental study. Section 3.3 uses a full-scale case study to test the applicability and benefits of the new systems by reusing pieces from existing buildings in Switzerland. Study results and limitations are discussed in Section 4. Conclusions are presented in Section 5.

2. Materials and methods

2.1. *Overview*

To develop, assess, and apply new floor systems made of cut RC CIP concrete, this study follows the methodology shown in Fig. 2. In parallel with the new floor development, the study starts with developing a procedure to calculate the allowable span for a piece cut in a continuous slab to be reused as a simply-supported slab in a new structure. This span is obtained using conventional analytical methods for reinforced concrete structural assessment. Building on the results obtained with this procedure, new-floor system concepts are developed during an iterative design process. Iterative design is commonly used in construction research as it enables progressive solution generation for complex problems (Wynn and Eckert, 2017). To understand and assess their design and environmental potential, the new-system concepts are then applied to a large set of donor and receiver combinations: design solutions are simulated, and environmental impacts are calculated. The parameterisation of the simulations allows for identifying the role of each parameter in the results. The result granularity helps understand the relevance of the proposed systems for given donor and receiver combinations and thus supports early decision-making. The environmental impacts are assessed using Life-Cycle Assessment (LCA), a reference method for accounting and comparing environmental impacts supported by ISO standards (International Organization for Standardization, 2006a; 2006b) and appropriate when accounting for different life-cycle stages of buildings and materials, including reused components (De Wolf et al., 2020). Facing the growing environmental crises, benchmarking the environmental impacts of new solutions during early

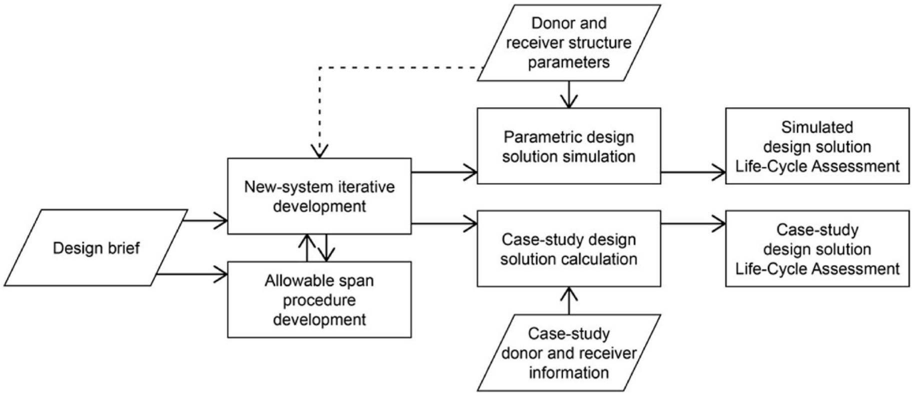


Fig. 2. Methodology flowchart.

development phases is essential for efficient solution development and implementation.

2.2. Scope and design brief

This study focuses on the preliminary design of floor systems that reuse as-cut RC pieces extracted from continuous CIP RC slabs. The study scope is limited to the preliminary design and environmental assessment of new floor systems that meet the following design intents:

- The new floor systems reuse pieces cut from continuous unidirectional 2 to 8-m-long CIP RC slabs from housing or office donor buildings. These donor slabs are assumed to represent a significant share of today's discarded RC slabs in many countries, including Switzerland.
- The new floor systems use RC pieces carefully extracted from donor structures, typically using circular diamond saws, with a tolerance of 2 cm on the intended dimensions.
- The RC pieces are reused as-cut, without strengthening or keying, to simplify and accelerate the reconstruction process. Reusing as-cut pieces aims to reduce complex, costly, and time-consuming operations on the pieces. Hence, the cut RC pieces are reused as simply-supported unidirectional slabs in the new systems. Cut pieces must thus have a structural capacity high enough to withstand every new action effect, including larger bending moments.
- The deconstruction, preparation, and reassembly operations should require only standard tools, such as regular trucks and lifting equipment, to ensure low construction costs. Therefore, the width of the reclaimed RC pieces does not exceed the width of a regular truck (2.5 m), and their length does not exceed the span of the donor floor, assumed to be always shorter than the length of a regular truck. The total weight of the piece is low enough to be lifted by regular lifting equipment. Nevertheless, the RC pieces must be cut as long as structurally possible to reduce the repetition of operations on the reclaimed pieces and the number of new connections and thus costs (Küpfer et al., 2022).
- The new systems are used in new housing and office buildings with regular loading situations and floors spanning between 2 and 8 m.

Design calculations are here made according to Swiss standards (SIA standards 260, 261, 262, 263, and 269, as listed in (SIA, 2013a)) and apply to the preliminary design phase. At this stage, assumptions regarding the reused slabs are based on knowledge of concrete construction history, general architectural and structural drawings, i.e., structural layout and overall dimensions, and basic donor-structure information, i.e., construction period, design use, and location. The slabs are assumed to be in good structural condition, which is usually the case in countries like Switzerland because (1) buildings are mostly discarded for reasons other than their structural state (Aksözen et al., 2017) and (2) slabs are generally protected from weathering by the building envelope and finishing.

2.3. New-system design method

The first steps of the study include developing new systems that reuse cut CIP RC pieces matching the design brief. This step is carried through an iterative design process combining existing-structure knowledge, static considerations, and architectural and structural design:

- Existing-structure knowledge supports the elaboration of solid hypotheses regarding the donor structures.
- Static considerations are used to analyse the bending, shear, and deflection capacities of reclaimed RC pieces in the new systems and verify their compliance with the current standards.
- Architectural and structural design provides a critical perspective on the space, aesthetics, and construction processes implied by the new systems.

Systems are iteratively drafted and discussed regarding structural efficiency, construction ease, and aesthetics. Successive design and examination rounds are repeated until conceptual system designs match all design-intent requirements. Selected conceptual systems that, together, allow any combination of donor and receiver-structure features are eventually detailed. The selected systems not only match the design intent but also require fewer new materials and allow the reuse of the longest as-cut RC pieces while requiring a simple construction sequence.

The definition of a procedure to estimate the allowable span of the cut RC pieces for reuse as simply-supported elements supports the design process for the new system. This allowable span must be studied due to the change of static systems between donor slabs and the new systems. Action effects between the donor continuous CIP slab and the cut and simply-supported reused slab pieces must be carefully accounted for.

As static systems involve simply-supported unidirectional elements, four structural verifications are accounted for in the definition of the allowable span: the bending and shear resistances (at ultimate limit states) and the short- and long-term deflections (at serviceability limit states), following current RC design standards in Switzerland. These verifications depend mainly on the RC slab properties, i.e., reinforcement steel bar diameter and spacing, steel yield strength, and slab thickness, as well as new use actions, e.g., additional self-weight and live loads. Slab thickness is assumed to be a known geometric property. Yield strength of steel reinforcement bars and concrete grade are taken from the standards for existing structures (SIA 269). The quantity of reinforcement steel bars is estimated based on the highest values between (more details provided in Section 3.1.2):

1. The reinforcement area needed to resist initial design stresses in the donor structure;
2. Minimal reinforcement requirements to avoid cracking as defined in the design standards at the donor construction time.

As this study focuses on the preliminary design phase, it does not include some local verifications, such as shear actions at the anchorage. Verifications are only made at the structural-element scale, and actions on the building scale, i.e., seismic and wind horizontal loads, have not been considered as they depend on the entire structure. Nonetheless, the connections proposed in Section 3.1.3 have been conservatively designed based on typical seismic actions in Switzerland. Thus, these simplifications will likely not significantly affect the comparative results presented in Sections 3.4.2 and 4.1, as the horizontal-loading verifications are typically not critical in Switzerland. The fire resistance concept of the proposed systems builds on the existing properties of the cut RC slabs and the newly added fire-proof coating of steel components. Finally, in terms of acoustic performance, the proposed systems are considered comparable to that of a new RC flat slab, ruling out the need for a thicker or different screed.

It is assumed that the donor buildings were correctly designed based on standard prescriptions at construction time. This study considers Swiss RC design codes from 1956 to today. Minimum reinforcement quantity is assumed based on past construction standards, notably the Swiss concrete construction code since 1956 (SIA, 1956) that requires a minimum reinforcement rate of 0.2 % of the slab cross-section area, while the steel yielding strength is taken in SIA 269 (SIA, 2011b). It is also assumed that the bottom-layer reinforcement of the donor slab is homogeneous and was not reduced near the support, which is the current practice in the country for short and medium-span slabs. The study is limited to preliminary design. Material and structural properties must be further verified on a case-by-case basis at further project stages with different testing techniques, as investigated by Devènes et al. (2023).

2.4. Parametric analysis

2.4.1. Design parameters

A parametric study is conducted to analyse the influence of selected design parameters on the new-system design solutions and their environmental impacts for a large set of donor and receiver structures. Design solutions are simulated for all combinations of seven design parameters listed in Table 1. The parameters cover the main characteristics of the donor and receiver structures. The resulting 20′280 combinations confirm the applicability of the new-system concept to a large number of reuse scenarios between donor and receiver buildings in Switzerland.

2.4.2. Life-cycle assessment methodology

The parametric analysis includes the comparison of the upfront environmental impacts of the simulated design solutions reusing RC floor systems with that of conventional flat RC slabs, the prevalent floor type in Swiss buildings. The comparison is made through a process-based Life-Cycle Assessment (LCA) using a cut-off allocation approach (Schrijvers et al., 2016). The same LCA method is used to assess the impacts of a full-scale case study (Section 3.3).

The functional unit is the linear spanning distance (measured in meters) of a 1-m-wide fragment of a load-bearing floor system for a housing or office building constructed today in Switzerland, which, in the conventional construction scenario, also includes the disposal of the equivalent material that is not reused. Non-structural layers of the floor systems (floor finish, screed, insulation, ceiling finish) are excluded from the functional unit and considered irrelevant for the comparison because they would be similar in all floor systems studied. The compared solutions are designed for the same expected service duration. The reused-RC system thus reuses only slabs that are not degraded. Moreover, mortar joints protect the cut reinforcement steel bars from corrosion.

Fig. 3 presents the LCA system boundaries:

Table 1
Design parameters for the parametric study.

Parameters	Value					Source
Donor-structure design use and respective live load [kN/m^2]	Housing 2		Office 3			SIA (2020)
Donor-structure construction period and respective steel resistance f$_{s,d}$ [N/mm^2]	1956–1967 300	1968–1988 390		1989–2023 435		SIA (2011a)
Donor-structure span (L_o) [m]	From 2 to 8, with 0.5 increments					–
Receiver-structure span (L_n) [m]	From 2 to 8, with 0.5 increments					–
Cut-RC-piece thickness (t) [m]	0.14	0.16	0.18	0.20	0.22	Local construction knowledge
Receiver-structure design use and respective live load [kN/m^2]	Housing 2		Office 3			SIA (2020)
Girder steel type and respective steel resistance f$_{y,k}$ [N/mm2] (applies to system B only)	New 335		Reused 235			SIA (2011a, 2013b)

- The assessment includes the end-of-life stage of the donor structure (modules C1-4 as defined by EN 15978 (European Committee for Standardization (CEN), 2011). If the new floor system does not reuse the components of the donor structure, its assessment accounts for the impacts of the conventional end-of-life of these components. If the new floor system reuses the components of the donor structure, module C1 corresponds to a selective deconstruction only, and modules C2-4 do not apply.
- The assessment includes the product and construction process stages (modules A1-5). Raw-material supply (module A1) is not considered for reused components, and the other modules (A2-5) are adapted to the specificities of the reused components and described later in this section.
- The assessment excludes the use and end-of-life stage of the new structure (modules B1-7 and C1-4).

Impacts are computed in terms of Global Warming Potential (GWP) [kgCO$_2$e]. The Appendix provides the GWP impact factors for each process included in the system boundaries, combining data from different sources. The Swiss KBOB database (KBOB, eco-bau & IBP, 2022) is used as an initial source of information for conventional construction processes and conventional material production and elimination. For processes related to the reuse of concrete, the work of Devènes et al. (2022) is referred to, in addition to complementary technical information provided by de-/re-construction-industry companies. Factors related to reused steel girders are inferred from Brütting et al. (2020), which relies on several databases, including Ecoinvent (Ecoinvent, 2019).

Regarding the reused concrete (plain blue lines in Fig. 3), the selective deconstruction (module C1) of concrete includes the shoring of the structure, the sawing of the concrete pieces, and the lifting of the cut RC pieces. Concrete sawing impacts include those caused by the electric consumption during sawing and a proportion of the impacts caused by the manufacture, wear, and elimination of the sawing disc and the machinery, based on the respective service duration. The impacts of manufacturing tiny quantities of synthetic diamond are assumed proportionally very low and are neglected when considering the steel disc wear. For the shoring of the structure, the study neglects the wear of the struts, as they are considered reusable over a very large number of uses, but includes the impacts of their transportation from storage and back and their lifting. The piece lifting impacts include the electric consumption of the crane but neglect the crane installation as it would have been needed on both construction sites, whatever the floor system is, and its wear during installation, as its use here represents only a fragment of its total service duration. The drilling impacts to install anchor bolts are not considered, as previous work showed the minor impacts of larger drilling operations (Devènes et al., 2022). The production of the anchor bolt is neglected as they are reused over a very large number of uses. Module A3 of the reused RC pieces solely includes drilling a hole in the piece corners. The drilling impacts are neglected as they are tiny, even in design solutions with far more drilling needs (Devènes et al., 2022).

Regarding the reused steel girders (dashed blue lines in Fig. 3), the impacts of selective deconstruction (module C1) include unbolting and lifting the steel profiles. The reconditioning impacts include sandblasting. For new and reused steel girders, the preparation (module A3) impacts includes welding (if necessary), degreasing, and adding a fireproof coating.

A 100 km transportation distance of steel girders between the deconstruction and the new construction sites is initially considered, and 0 and 100 km transportation distances are considered for concrete pieces. A sensitivity analysis of this parameter is conducted in section 3.2.4 to understand the exact influence of different transportation distance scenarios. The case study (Section 3.3) uses actual transportation distances.

The slabs used for comparison with the newly developed reused RC

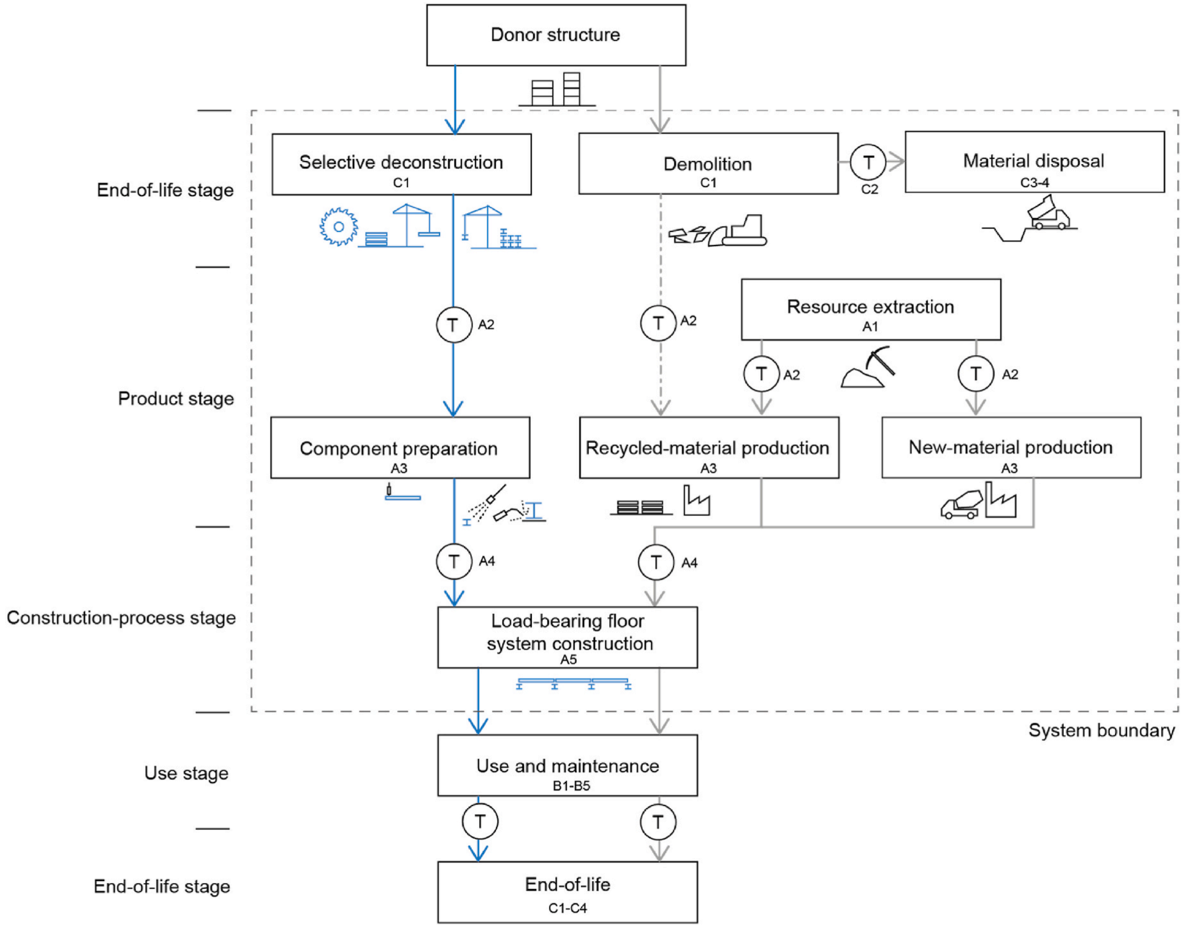


Fig. 3. LCA processes and system boundaries. Circled T's represent transport. The reused elements route is in blue, and the traditional manufacturing route is in black. Recycling impacts are allocated according to a cut-off approach. Numbering of modules according to EN 15978.

floor systems are newly produced flat cast-in-place RC slabs, which are conventional for Swiss construction practices. The flat slabs are one-way, simply-supported slabs also supported by walls. Regular timber formwork, concrete (C25-30) and steel reinforcement bars ($f_{s,d} = 435$ N/mm^2) from the Swiss market are considered. The flat slabs are designed for the same variations of span and load, following current Swiss standards (SIA, 2013a, 2013c, 2020). The slabs are checked for both ultimate limit states and serviceability limit states, and are designed to transfer seismic loads to the vertical supports, similar to the reused slabs presented in the previous section. The resulting slab thicknesses are 18 cm for spans below 4 m, 20 cm until 6 m, and 22 cm until 8 m. The reinforcement steel bar rate is 1.5%, as commonly estimated in practice for this structure type at the preliminary design stage.

3. Results

3.1. New floor systems

3.1.1. Overview

This section presents the two new floor systems – System A and System B (Figs. 4 and 5) – that reuse as-cut RC pieces extracted from continuous CIP slabs. The two systems build on the existing structural properties of the donor RC structures and avoid new strengthening. Together, they provide a design solution for a large set of design parameter combinations regarding both donor-structure and receiver-design characteristics, later described in Section 3.2.1.

The length of the pieces to be cut in the donor structure and reused in the receiver structure is restricted by their capacities to withstand the design loads in their new configuration. The cut pieces are then reused in one of the two systems, depending on the receiver-structure span L_n:

- System A reuses the cut RC pieces as primary elements to span L_n. Connections can be provided in various ways. In this study, they consist of newly manufactured steel angles.
- System B reuses the cut RC pieces as secondary elements over girders that cover L_n. Girders can have multiple designs. In this study, they are chosen to be standard H-shape steel profiles, either newly produced or reused. Steel has been chosen as the material for the primary girders due to its high mechanical performance and the H-shape profiles for their efficient cross-section and availability on the reuse market.

In both cases, the pre-existing resistance of the slab constrains the maximum allowable length L_a that the slab can have once cut and installed in the new system. L_a depends on the capacity of the slab, the actions and constraints during the reuse process (lifting, transportation, assembly), and L_n. Therefore, quantifying L_a is needed to define whether a given slab is best fit for reuse in System A when $L_a \geq L_n$, or in System B when $L_a < L_n$.

The following sub-section 3.1.2 provides a straightforward calculation procedure for L_a. Sub-section 3.1.3 then develops construction details. Sub-section 3.1.4 eventually discusses the benefits and constraints of both systems. In the following, indices o refers to the old donor structure, c to the cut RC pieces, and n to the new receiver structure.

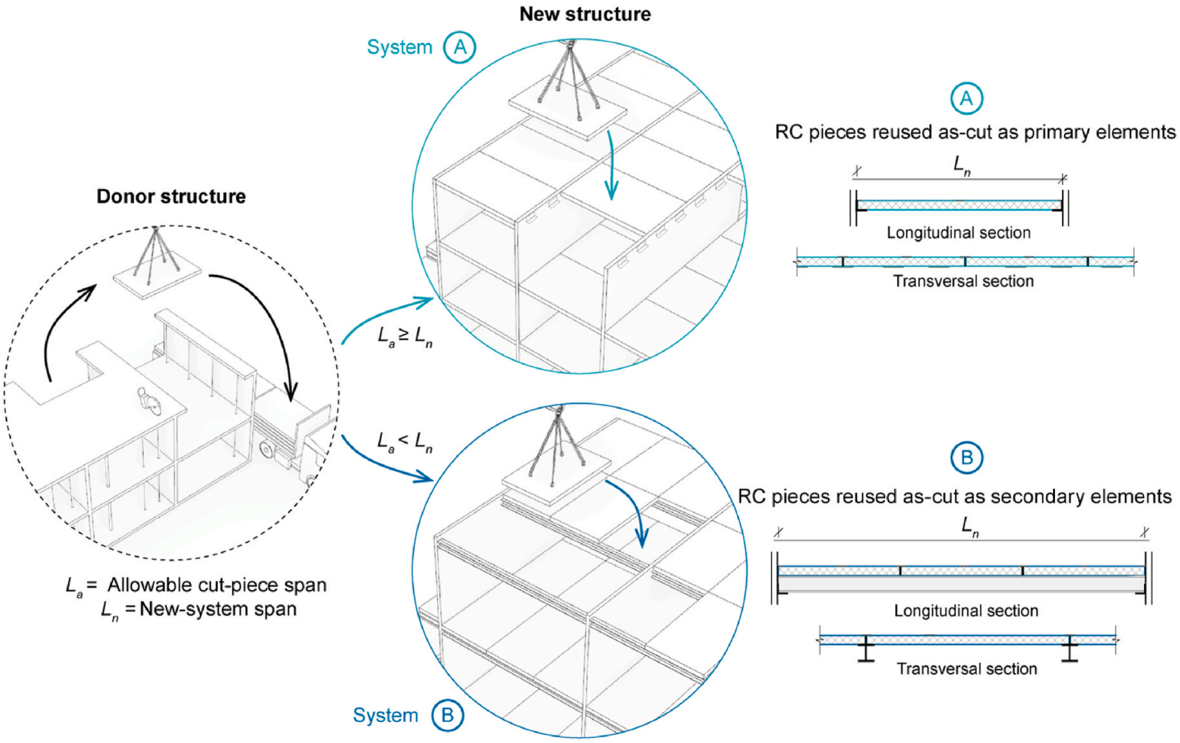


Fig. 4. Concept of the reused RC floor systems: RC pieces are cut from existing buildings undergoing demolition and reused as primary (System A) or secondary (System B) elements in new building floors.

Fig. 5. Low-angle views of the two systems: (a) System A and (b) System B.

3.1.2. Maximum allowable spans for cut RC pieces

This section introduces a procedure to determine L_a, i.e. the maximum allowable span for which the reused RC piece can withstand the new actions in the new system. L_a is the sum of the structurally allowable span and an extra length L_s needed to build the support of the RC pieces in the new system, i.e. steel angles, plates or flange, here admitted to equal 10 cm for each support. Bending, shear, short- and long-term deflections (involving crack sections and creep) have been considered. Due to the small spans, elastic deflections remain small, and deflections are thus not critical. Given the piece span, the linear support at both ends and the distributed live loads, shear actions remain limited and are not critical. For all verifications within the parametric study, the bending verification was critical and is the only one detailed below.

L_a is determined by the following conditions:

1. The total load level in the receiver building $q_{n,d}$ (including design values of the live loads and self-weight);
2. The static system of the new structure, which influences the maximum bending moment $M_{Ed,a}$ occurring in the cut slab;
3. The bending resistance of the cut RC concrete piece $M_{Rd,a}$.

In this study, it is assumed that $q_{n,d}$ is linearly distributed, and that the receiver static system is a simply-supported slab. The following verification is needed to ensure structural safety:

$$M_{Ed,a} = \frac{1}{8} q_{n,d} * L_a^2 \leq M_{Rd,a} \Leftrightarrow L_a \leq \sqrt{\frac{8}{q_{n,d}} M_{Rd,a}} \quad (1)$$

While $q_{n,d}$ is known by designers, $M_{Rd,a}$ is often unknown because of missing original construction drawings or the impossibility of performing destructive or non-destructive tests on the slab. Nevertheless, the next paragraphs show how $M_{Rd,a}$ can be estimated at the preliminary design stage from structural information generally available and old structure codes.

Bending resistance $M_{Rd,a}$ mainly depends on the steel reinforcement of the cut slab and the slab thickness. Two types of steel reinforcement influence the bending resistance: tensile reinforcement or minimum reinforcement. While tensile reinforcement in the original system is a function of expected bending actions, minimum reinforcement is meant to prevent cracking. Minimum reinforcement $A_{s,m}$ is also designed with standard steel-bar diametres (e.g. 8 or 10 mm) and spacings (150 mm) and must be, at least proportional to a steel area ratio ρ_m of the slab cross-section. For instance, in Switzerland, a minimum ρ_{min} of 0.2 % has been required by code since 1956 (SIA, 1956, 2013c).

Thus, $M_{Rd,a}$ depends on what prevails between bending resistance $M_{Rd,a,m}$ provided by minimum reinforcement and bending resistance $M_{Rd,a,t}$ provided by tensile reinforcement (Fig. 6):

$$M_{Rd,a} = \max\left(M_{Rd,a,m}; M_{Rd,a,t}\right) \tag{2}$$

Likewise, combining Equations (1) and (2), L_a must then be smaller than the greatest value between $L_{a,m}$, the maximum allowable span when only minimum reinforcement is considered, and $L_{a,t}$ the maximum allowable span when only tensile reinforcement is considered:

$$L_a \leq \max\left(L_{a,m}; L_{a,t}\right) \tag{3}$$

where:

$$L_{a,m} = \sqrt{\frac{8}{q_{n,d}} M_{Rd,a,m}} + L_s \tag{4}$$

$$L_{a,t} = \sqrt{\frac{8}{q_{n,d}} M_{Rd,a,t}} + L_s \tag{5}$$

Regarding minimum reinforcement, $M_{Rd,a,m}$ is independent of the donor span L_o and is estimated based on minimum reinforcement area $A_{s,m}$, slab thickness h, and steel yield strength $f_{s,d}$, deduced from old standards (SIA, 2011a):

$$M_{Rd,a,m} = A_{s,m} f_{s,d} 0.81h \tag{6}$$

Regarding tensile reinforcement, $M_{Rd,a,t}$ is equal to or larger than the maximum bending moment $M_{Ed,o}$ occurring in the donor building. It thus depends on the formerly applied load $q_{o,d}$ and the original static system that is assumed as a continuously-supported slab of span L_o, hence:

$$M_{Rd,a,t} \geq M_{Ed,o} = \frac{1}{24} q_{o,d} L_o^2 \tag{7}$$

It is conservatively assumed that $M_{Rd,a,t}$ is equal to $M_{Ed,o}$. Combining Equations (5) and (7) hence provides:

$$L_{a,t} = \sqrt{\frac{q_{o,d}}{3q_{n,d}}} L_o + L_s \tag{8}$$

From this point, it is possible to determine L_a function of L_o for a slab with a given thickness, construction period, and donor- and receiver-structure use (Fig. 7). For a given slab, $L_{a,m}$ is constant and independent from L_o (Equations (4) and (6)) and $L_{a,t}$ is linearly increasing with L_o (Equation (8)). Consequently, $L_{a,m}$ will be smaller than $L_{a,t}$ up to a certain length $L_{o,t}$ from which tensile reinforcement will become prevalent. $L_{o,t}$ is obtained by computing the intersection $L_{a,m} = L_{a,t}$ from Equations (4) and (8)):

$$L_{o,t} = \sqrt{\frac{24}{q_{o,d} M_{Rd,a,m}}} \tag{9}$$

Thus, in summary, three scenarios exist to determine L_a (Fig. 7):

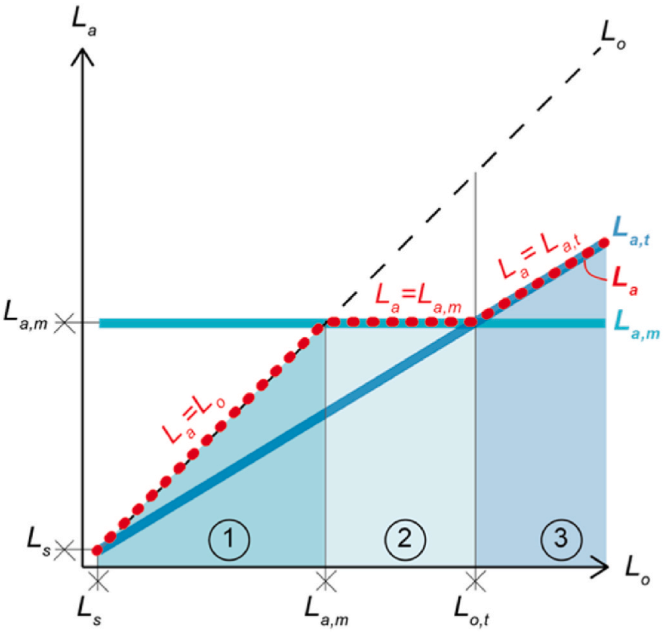
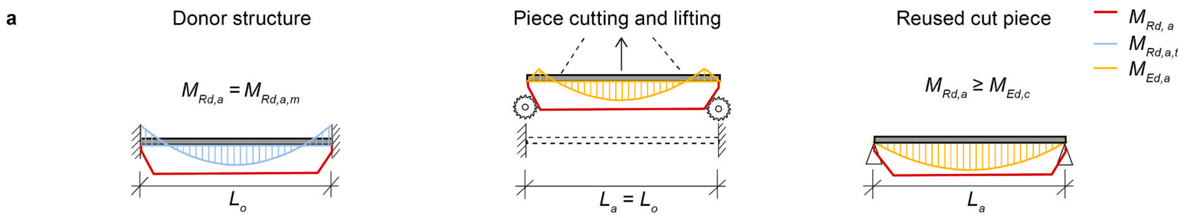
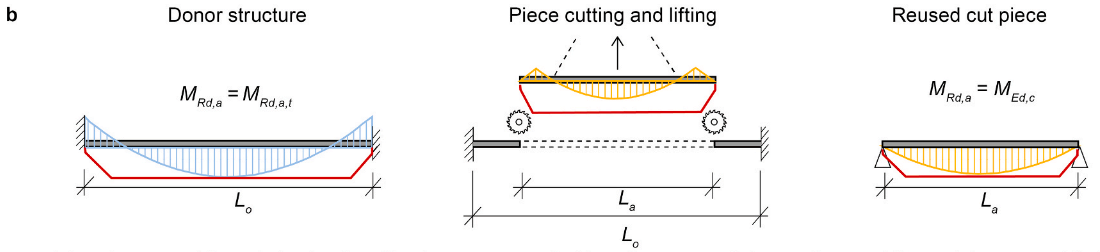


Fig. 7. Maximum allowable span L_a as a function of the initial span L_o in the donor-building. The distance between the red line and the dashed black line corresponds to the necessary length to cut.



The resistance provided by the minimum reinforcement allows cutting and reusing pieces as long as the donor span ($L_o \leq L_a$)



The pieces must be cut shorter than the donor span so that bending moment does not exceed the resistance provided by tensile reinforcement when reused ($L_o > L_a$)

Fig. 6. Two situations arising when considering the maximum allowable span L_a as a function of reinforcement: (a) minimum reinforcement prevails or (b) tensile reinforcement prevails.

- (1) When $L_o \leq L_{a,m}$, there is no need to cut the slab, the entire span can be reused, its bending capacity is governed by minimum reinforcement;
- (2) When $L_{a,m} < L_o \leq L_{o,t}$, the slab must be cut to a length equal to $L_{a,m}$, its bending capacity is governed by minimum reinforcement;
- (3) When $L_{o,t} < L_o$, the slab must be cut to a length smaller than $L_{a,t}$, its bending capacity is governed by tensile reinforcement

In all scenarios, the span reduction can be expressed as ratio α:

$$\alpha = \frac{L_a}{L_o} \tag{10}$$

In the third scenario, α is renamed α_t and the cut length equals $L_o - L_{a,t} = (1 - \alpha_t)L_o - L_s$, where:

$$\alpha_t = \frac{L_{a,t}}{L_o} = \sqrt{\frac{q_{o,d}}{3q_{n,d}}}L_o + L_s \tag{11}$$

Fig. 8a presents numerical values for $L_{a,m}$ (Equation (4)), i.e., the span until which no shortening is required, thanks to the resistance provided by the minimum reinforcement. Numerical values are computed for several donor slab types and reuse cases: two typical live loads ($q_{o,l,k}$ *or* $q_{n,l,k} = [2;3]\ \mathrm{kN/m^2}$, respectively housing and office distributed live loads in the Swiss code (SIA, 2020)), five common donor slab thicknesses ($h = [14;16;18;20;22]$ cm), and three construction periods of donor slabs ($[1956;1967]$; $[1968;1988]$; $[1989;\cdots]$), each characterised by a typical steel resistance ($f_{s,d} = [300;390;435]$). Overall, $L_{a,m}$ values range between 3.2 and 5.6 m and increase with more recent and thicker slabs. If the cut-RC pieces are 18 cm or thicker, the span allowed for reuse without shortening exceeds 4 m for any design parameters combination loading and construction period. This means that any slab that is at least 18-cm thick and that spans less than 4 m in the donor building ($L_o < 4\mathrm{m}$) is, at the preliminary design stage, considered reusable over their entire length without shortening, thanks to minimum reinforcement requiring at least 10-cm diameter steel bars spaced every 150 mm. Thinner slabs that are at least 14-cm thick can also always be reused as long as they span less than 3 m ($L_o < 3\mathrm{m}$), thanks to minimum reinforcement requiring at least 8-cm diameter steel rebars spaced every 150 mm. This is an important finding since it is likely that a large part of RC building structures available for reuse today fall within one of the two categories (18-cm or thicker, or 14-cm or thicker).

Fig. 8b details the numerical values of α_t for common values of donor structure live loads ($q_{o,l,k} = [2;3]\ \mathrm{kN/m^2}$), receiver structure live loads ($q_{n,l,k} = [2;3]\ \mathrm{kN/m^2}$), and self-weight depending on 5 typical slab thicknesses ($h = [14;16;18;20;22]$ cm), assuming similar dead loads between donor and receiver structures. Overall, $\boldsymbol{\alpha}$ stands between 55 and 64 %, with the highest values obtained when total loads applied on the receiver structure are lower than those applied on the donor ones, e. g., when pieces extracted from an office donor building are reused into a new housing building. If $q_{o,d} \approx q_{n,d}$, then $\alpha \approx 0.58$, which means that all donor slabs thicker than 18 cm and longer than $L_{o,t} = L_{a,m}/\alpha = 4/0.58\mathrm{m} = 6.9$ m could only withstand a new span equal to 58 % of the original span in the donor building. In other words, for donor slabs longer than 6.9m, a minimum of 42 % material loss is expected unless the slab is strengthened by other means.

In summary, it is deduced that shorter donor slabs are to be reused as-is as a priority and that longer donor slabs are to be cut in half and reused as two separate short slabs, which would avoid a ≈ 42 % material loss.

3.1.3. *Construction details*

The construction process of the new systems starts with the selective deconstruction of the reused RC pieces (Fig. 1). This step begins with shoring up the donor structure. Then, the pieces are cut from the donor floor slab using a circular saw and lifted using techniques comparable to those used to install prefabricated RC slab elements. If not reused on the same site, the RC pieces are loaded on a truck and directly transported to the new construction site, where a hole is drilled in each corner.

On the new construction site, the vertical supports are installed first. In this study, the supports are assumed to be installed on walls. Little adaptation is required to install them on other types of vertical supports. In system A (Fig. 9a–b), the supports are newly-produced steel angles. The angles are coated with fire-proof painting. They have the same height as the cut RC piece and are symmetrical. In system B (Fig. 9c–d), the supporting girders are bolted on newly produced steel angles fixed on the walls. The girders are either newly-produced or reclaimed from an old structure and reused. In both cases, the top girder flange must be at least 20 cm wide to support the edge of the cut RC pieces (10 cm each) and allow the construction of the connection detail. If the top-flange width is smaller than 20 cm, a new 20 cm wide steel plate is punctually welded on the top flange of the girders to support the edges of the two RC pieces.

For both systems, once the connecting supports are fixed, the cut RC pieces are lifted from the ground and placed as is on the supports previously topped with an elastomer layer. Joints between cut RC pieces are then filled with mortar. On average, joints are estimated to be 2 cm wide, similar to the largest cut tolerances with diamond-saw blades. Polyethylene is used to secure mortar filling. Finally, steel plates connecting the cut RC pieces together and to the girders ensure the lateral stability of the RC pieces and the transfer of typical seismic horizontal

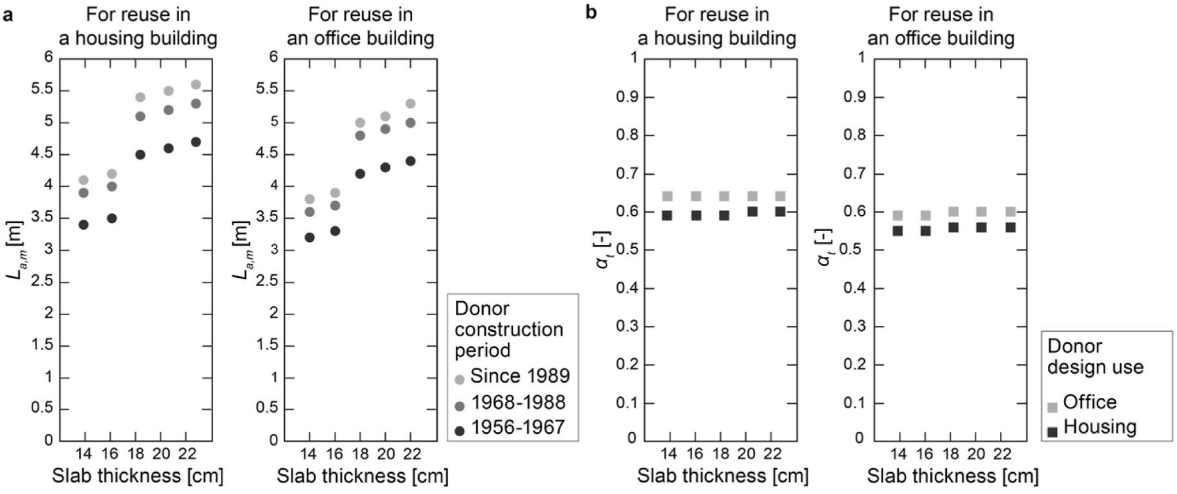


Fig. 8. (a) Spans that allow the cut piece to span as long as the donor and (b) ratios between allowable cut piece span over donor span, for longer spans.

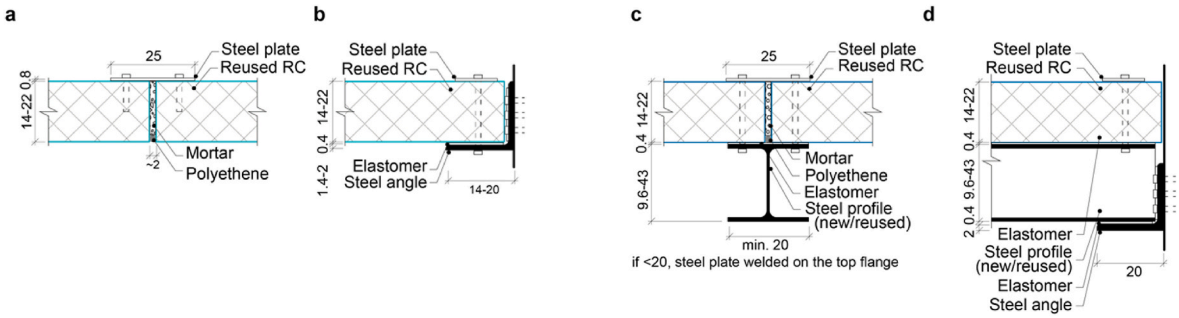


Fig. 9. Details of the reused RC systems: transversal and longitudinal sections of Systems A (a,b) and B (c,d), respectively.

loads for Switzerland. Finally, bolted steel plates connect the cut-RC-pieces to each other and with the girders.

3.1.4. Benefits and constraints

Overall, the new floor systems ensure the high-quality reuse of discarded RC slabs, capitalising on their existing capacities. The new systems are engineered to perform as well as any standard floor systems. Still, their main advantage is that their construction does not necessitate any new materials except for connectors and, if not reused, girders for System B. In addition, the two systems enable quick and nearly entirely dry construction (except for some mortar in the 2 cm joints between slabs) and require only standard de-/re-construction techniques and tools. Finally, the systems are designed with reversible connections: steel elements can be unbolted, and the mortar joints hydro-jetted. The slabs are hence reusable for an additional use cycle into new floors with similar or shorter spans by trimming the elements further or into longer spans supported by new girders.

However, the approach is currently limited by the prevalence of demolition habits over careful deconstruction of discarded structures, which challenges the procurement synchronisation between the donor and receiver structures. If a structure is about to be discarded but the receiver structure remains uncertain, the donor structure could be cut into pieces of the maximum span allowed for the likeliest load case, and the cut RC pieces eventually trimmed when the receiver structure design is set. The results of this study show that existing RC slabs spanning 3.2–5.6 m, depending on slab thickness and construction year, could be cut and reused over their entire original span for both housing and office receiver buildings. It is thus likely that a large share of the discarded building stock could be cut in full-length elements, independently of the receiver use case.

The systems introduced in this section are efficient and innovative design solutions to reuse discarded CIP RC slabs. In addition, System B can accommodate nearly any span and geometry by adapting the design of the girders. Therefore, these new floor systems meet all criteria of current construction practice and can technically be implemented at a large scale, provided careful deconstruction of structures is more widely adopted.

3.2. Parametric design and environmental analyis

3.2.1. Simulated design solution overview

Of all simulated designs, 35% use System A ($L_a \geq L_n$) and 65% use System B ($L_a < L_n$). The latter rely on a large set of H-shape girder profiles (Fig. 10). Employing newly produced profiles generally allows for smaller sections than reused profiles due to the higher yield strength considered (Table 1). The most used profiles for System B are HEA300 for both newly produced and reused elements. This type of steel profile is widely used in Switzerland, which should favour its supply.

Long systems require long and rather large steel profiles, which may be challenging to supply rapidly in a short material-hunting radius. Thus, the environmental analysis includes a sensitivity analysis of environmental impact as a function of the reused-material transportation distance (Section 3.2.4).

3.2.2. RC span reductions

As detailed in Section 3.1.2, RC span reductions, measured as α (Equation (10)) are often required in order to ensure that the donor slab fulfils all structural requirements in the receiver building. Fig. 11a presents the reusable cut span ratios α for all generated donor-receiver combinations. Overall, α ranges between 55 % and 100 %. For donor spans up to 3 m, α equals 100 %, meaning the donor slab can be reused over its entire length in the new systems ($L_a = L_o$). On average, α linearly decreases from 100 % to 61% for spans greater than 3.5 m. Beyond 5.5 m, all generated slabs must be shortened to be reused in the new systems. Up until 8 m at least, α is always greater than 55 %.

Fig. 11b–d plots the distribution of α for various slab thicknesses,

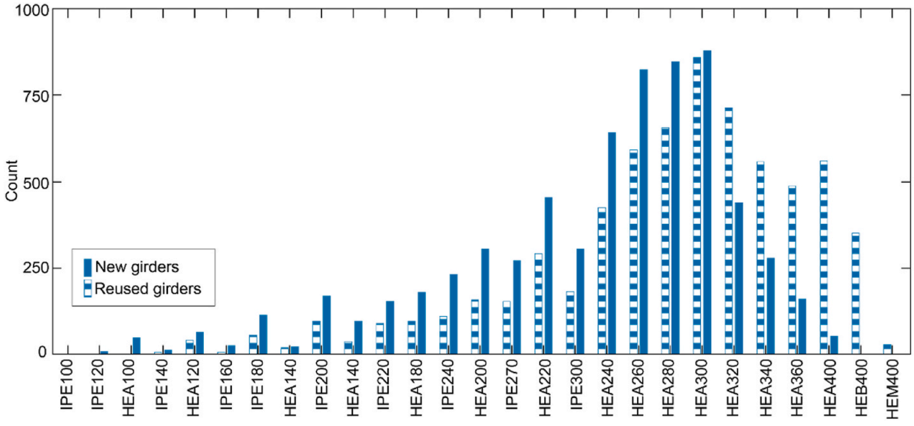


Fig. 10. Distribution of girder steel profiles for design solutions with System B.

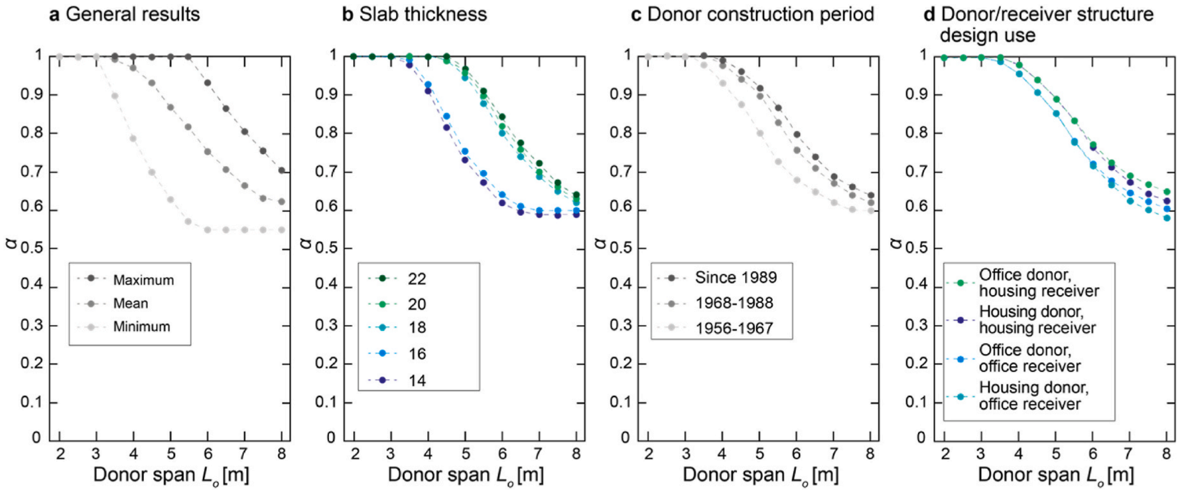


Fig. 11. Ratio α between the allowable cut piece span and the donor span. Overall maximum, mean and minimum values (a) and average values for selected design parameters (b–d).

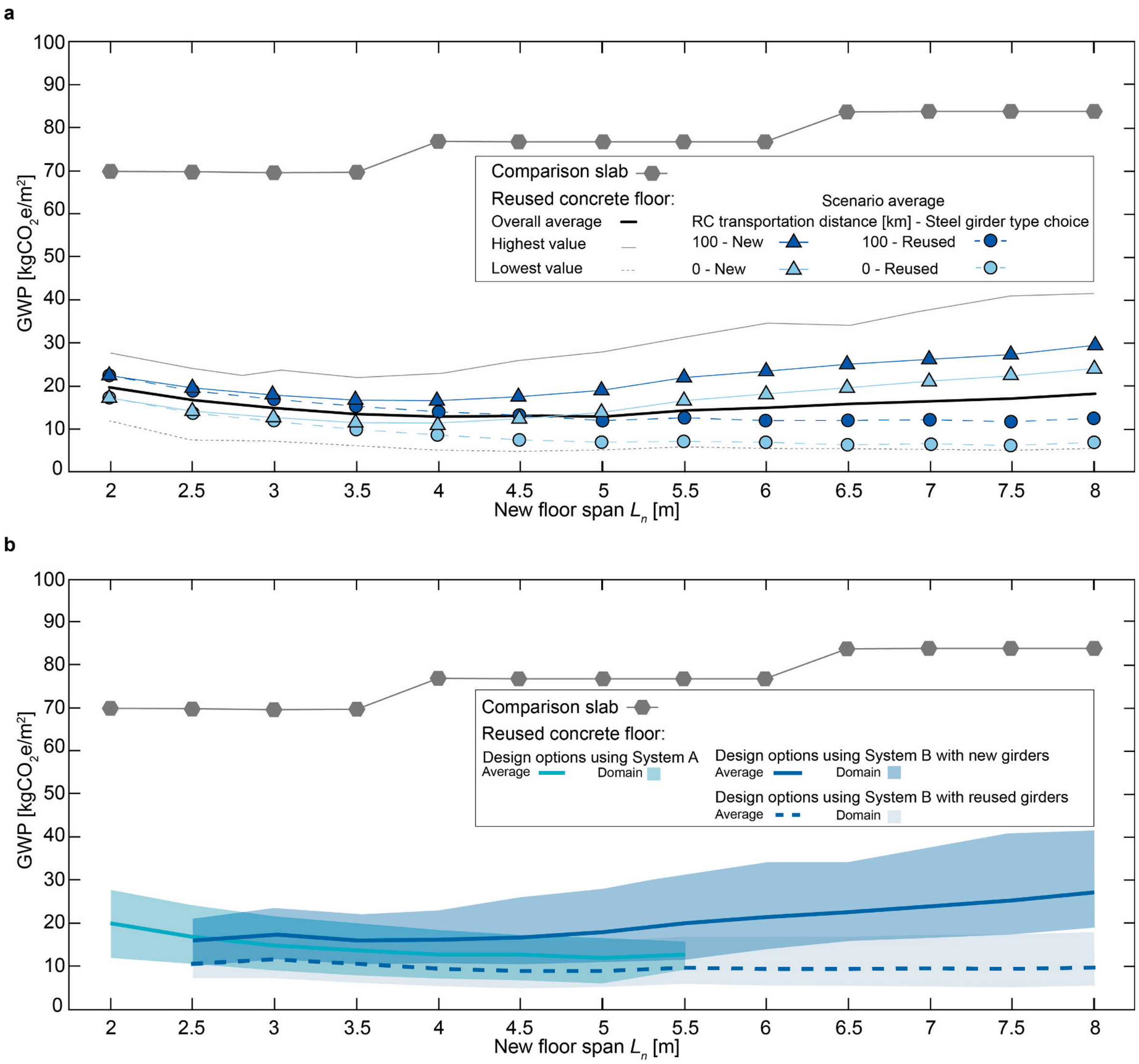


Fig. 12. GWP reductions obtained by reusing concrete slabs when compared with a new RC flat slab, considering four scenarios. Each scenario combines a choice between 0 and 100 km transportation distance of RC pieces and a choice between new and reused steel girders.

donor construction periods and donor-/receiver-structure design use. For donor slabs longer than 3.5 m, a higher ratio is possible with thicker slabs (18–22 cm) than with thinner slabs (14–16 cm), with differences up to 25 % for similar spans. The construction year, which influences the resistance of steel reinforcement, affects α. For similar spans, the newest slabs (built since 1989) allow ratios up to 14 % bigger than the oldest slabs (built between 1956 and 1967). As shown in Fig. 11d, α is only slightly influenced by uses in donor and receiver structure, although design live-loads are lower for housing buildings than office buildings. Reusing pieces cut from an office building into a housing building only allows a ratio up to 7 % higher than if pieces were reused from a housing to an office building.

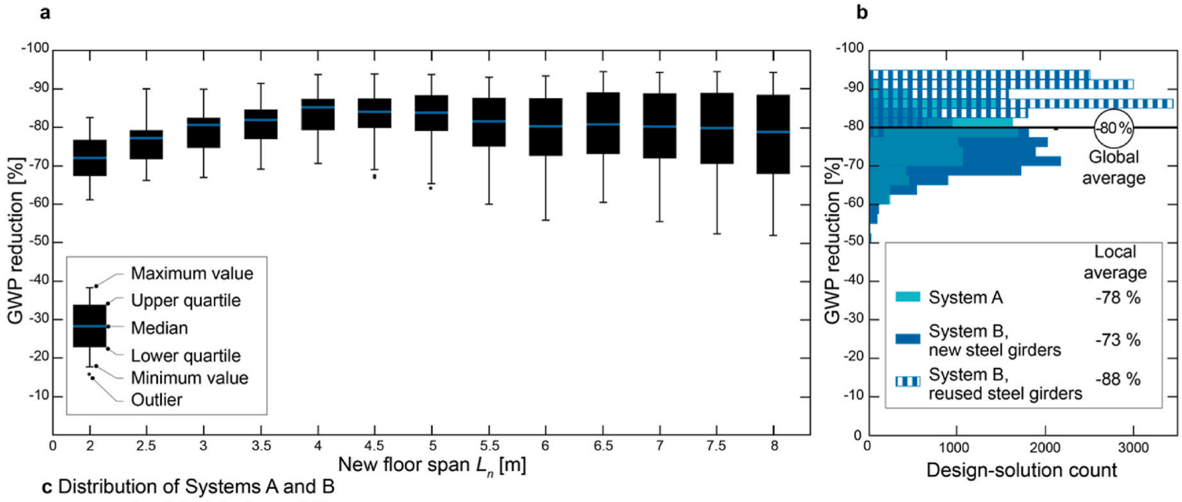
3.2.3. GWP savings

Results of the parametric LCA show that reusing RC slabs for building floors considerably reduces upfront greenhouse gas emissions compared to the conventional cast-in-place practice (Fig. 12, Fig. 13). The average GWP of all reused-concrete system simulations is 15 $kgCO_2e/m^2$ and their average GWP reduction compared to conventional RC flat slab is of 80 %. The GWP of the reused-concrete systems ranges between 5 and 41 $kgCO_2e/m^2$, while the conventional RC flat slab GWP ranges between 68 and 85 $kgCO_2e/m^2$ (Fig. 12). The latter range is comparable to others obtained for RC flat slabs in the literature (Jayasinghe et al., 2022a; Regúlez et al., 2023). For receiver structures spanning less than 4 m, all simulations range between 6 and 28 $kgCO_2e/m^2$, and results are not sensitive to the considered type of steel girders since System A is prevalent for such spans. Beyond 4 m of span, GWP differs increasingly depending on whether steel girders are reused or not: when steel girders are reused, GWP remains on average steady and below 13 $kgCO_2e/m^2$; when they are not, GWP increases linearly, up to an average of 30 $kgCO_2e/m^2$ if cut RC pieces are transported over 100 km. The increase is explained by the larger proportion of newly produced steel in those simulations. When reusing steel girders, all solutions have a GWP lower than 17 $kgCO_2e/m^2$. Globally, diminishing transportation by 100 km decreases the average GWP of all simulations by 5 $kgCO_2e/m^2$.

With the reused-concrete systems, GWP are reduced by 80 % in average compared to new flat slabs, with minimum reductions of 51% and maximum reductions of 94 % (Fig. 13a). The most significant median reductions are obtained for new systems spanning 4 m or longer, with median savings reaching up to 85 % (Fig. 13a). The smallest median savings are obtained for new floors spanning 2 m, with median savings of 72 %. A larger proportion of additional new materials in short-spanning systems explains this result. The worst single GWP reduction for each new floor span first increases from 2 to 4 m and then decreases until 8 m. The worst reduction (51 %) is obtained for simulations of new long-span floors (8 m) reusing thick (22 cm) and short-span (2 or 2.5 m) donor slabs over new steel girders (System B). Conversely, the largest reductions (92–94 %) are typically obtained for new mid-to long-span floor (4–8 m) reusing relatively thin (14–20 cm) mid-to long-span (4–8 m) donor slabs over reused steel girders (System B).

For solutions designed with System B, replacing newly produced steel girders with reused ones further decreases GWP reductions by 15 % on average (Fig. 13b). Indeed, solutions designed with System B and reused steel girders cause 88 % smaller GWP than the conventional RC slab. For solutions designed with System B but with newly produced steel girders, this average is 69 %; for solutions designed with System A, this average is 78 %.

Average GWP reductions are not sensitive to the donor-structure design load, its construction period, or the receiver-system design load since only differences smaller than 1.5 % are observed (Fig. 14d). However, results are sensitive to slab thickness, the donor-slab span, and the way girders are procured. Variations of up to 15 % are observed when slab thicknesses range between 14 and 22 cm (Fig. 14a), which is explained by the fact that emissions caused by transportation and steel girders production are reduced when reusing thinner slabs. Up to 9 % further reductions are obtained on average if long rather than short donor slabs are reused (Fig. 14b). Indeed, reusing long slabs generally reduces the number and proportion of connectors and other new materials. When System B is involved, building with reused rather than



c Distribution of Systems A and B among simulated design solutions

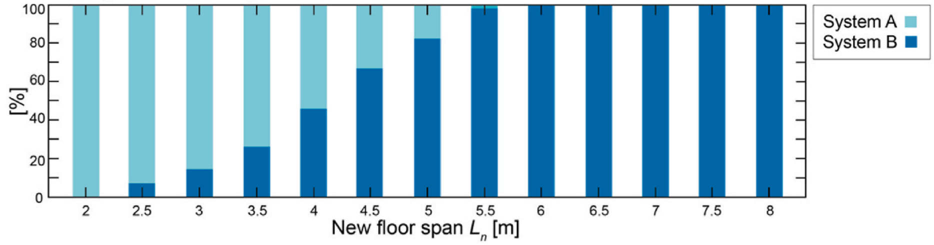


Fig. 13. Distribution of GWP reductions for each new floor span L_n while considering all parametric simulations.

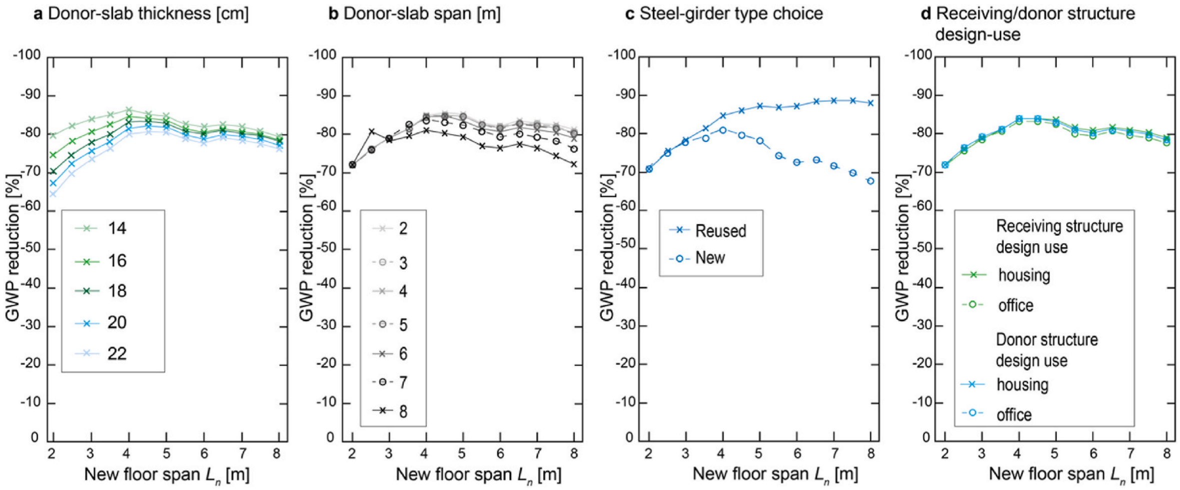


Fig. 14. Sensitivity of average GWP reduction for all simulated reused RC floors compared to flat RC slabs as a function of the new system span floor L_n for selected design parameters.

newly produced girders allows a maximum average additional reduction of 21 % for the same span (Fig. 14c). The additional savings are generally larger for the longest new systems as a larger proportion of girders is needed.

3.2.4. *Influence of transport distance*

Fig. 15a and b plot GWP and GWP reductions obtained with the reused-concrete alternatives when transportation distances of both the reused RC cut pieces and the reused steel girders are 0 or 100 km. Generally, results are nearly insensitive to transportation distance variations of reused steel since steel weighs significantly less than concrete in the system, and reused steel is used only in a subset of solutions. However, additional reductions of 7 % on average are obtained if the new system is built on the same site as the donor building (0 km transportation distance). Indeed, when reused concrete pieces are transported over 100 km or 0 km, GWP reductions average 76 % and 83 %, respectively. Maximum reductions are obtained for solutions using System B with reused steel girders, with average reductions of 85 % and 92 % when reused cut RC pieces are transported over 100 km and 0 km, respectively.

Fig. 15c plots the median, minimum, and maximum reductions for transportation distances varying from 0 to 2000 km while considering all simulated solutions. A quasi-linear decrease of GWP reductions is observed as transportation distance increases. Simulations show that reusing slabs always reduces GWP for transport distances shorter than 765 km, never reduces GWP for transport distances longer than 1766 km, and presents a 50 % chance of GWP reduction if transport distances are 1128 or 1275 km, depending on whether the design considers newly-produced or reused steel girders.

3.3. *Case study*

3.3.1. *Donor and receiver buildings*

A case study of RC slab reuse in an actual building is used to test the applicability of the conceptual new floor systems and measure the greenhouse gas emissions related to their implementation in a larger context. The case study involves the design of floors in a new office building. The floors span 3 and 6 m and are made of reused concrete pieces with, if necessary, steel girders extracted from two existing Swiss buildings:

- The donor building from which the RC pieces are reclaimed is a typical Swiss housing building constructed in 1980 in Geneva canton with CIP RC continuous 15-cm-thick slabs (Fig. 16a). The reclaimed slabs originate from the bedrooms, repeated in every flat on every floor and span 3.10 m.
- The donor building from which steel girders are reclaimed (Fig. 16b) is a sports hall built in 2017 in Vaud canton with various steel profiles and has been recently deconstructed. The steel-profile stock includes three H-shape steel profiles: HEA160, HEA320, and HEB300, with lengths up to 6 and 11 m.
- The new building is planned in Geneva canton, implying a maximum transportation distance of 20 km for the reclaimed cut RC pieces and 80 km for the reused steel girders.

3.3.2. *Design solutions*

The floors of the receiver building are designed by applying both types of floor systems while relying on cut slabs from the same donor building (Fig. 17): System A when receiver floors span 3 m; and System B when receiver floors span 6 m In the latter case, cut RC pieces are 3.1 m long and supported by newly produced HEA240 or reused HEA320 from the Swiss market.

The conventional comparative flat slab is designed according to current standard practices with a concrete grade of C30/37. The reinforcement bar quantities are calculated manually according to conventional Swiss engineering office practice. The 3-m slab is 18 cm thick, and manual reinforcement calculations recommend the equivalent of a 1.42 % reinforcement rate (B500B, $f_{s,d} = 435\ MPa$). The 6-m slab is 20 cm thick, and the reinforcement rate is estimated at 1.4 %.

3.3.3. *GWP reductions*

Reusing the concrete slabs saves up to 88 % of GWP compared to the construction of conventional RC flat slabs. Reusing involves a GWP ranging between 9 and 22 kgCO$_2$e/m^2, while constructing conventionally involves a GWP ranging between 67 and 74 kgCO$_2$e/m^2 (Table 2).

Compared to the production of 1′000 m^2 of newly-cast RC 18-cm flat slab, creating 3-m-long spans with reused slabs (Fig. 18a) not only avoids emitting 56 tons of CO$_2$e, but also avoids producing 408 tons of concrete, and while reusing no less than 375 tons of RC, which are diverted from conventional elimination routes. Most of the greenhouse gas emissions related to the production of the reused-concrete floor are due to the manufacturing of the connection details (87 %). 74 % is emitted for producing new steel elements (plates and angles) and 5 % for the mortar. The transportation of cut RC pieces is responsible for 8 % of GWP, while its sawing is only for 2 %. Less than 1 % of the floor system GWP is produced during the transportation of the new materials, the lifting of the cut RC pieces, or the shoring up of the old structure.

Building a 6-m-span floor with reused cut RC pieces on top of steel

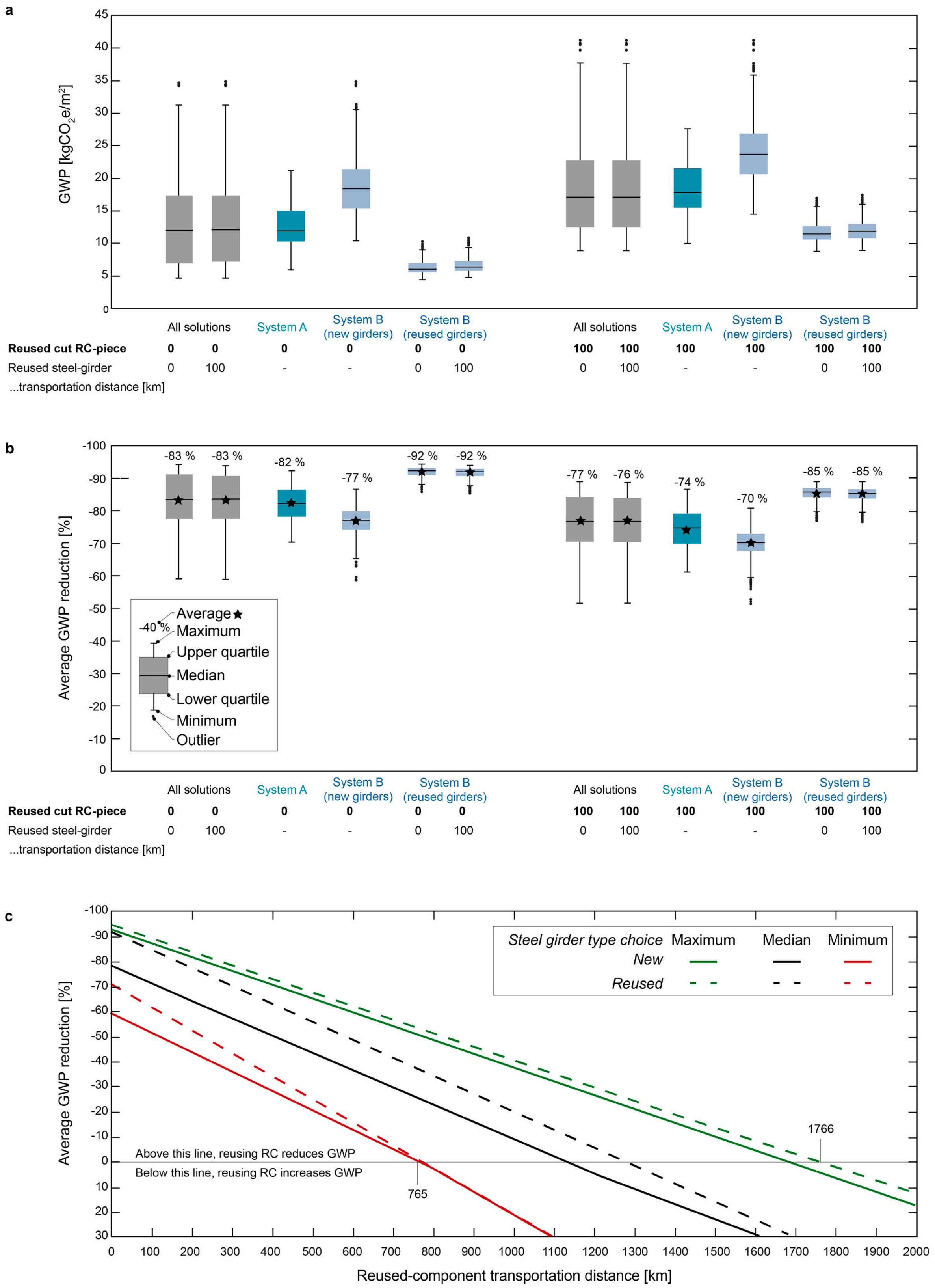


Fig. 15. Influence of the reused-component transportation distance on (a) the GWP and (b,c) GWP reduction of the reused RC systems compared to conventional RC slabs for all simulated design solutions.

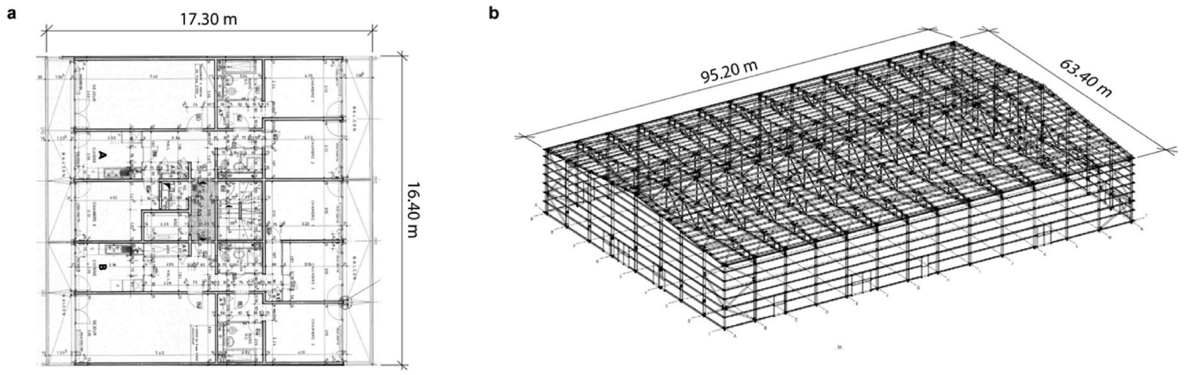


Fig. 16. Donor buildings for the case study: (a) RC donor building block (typical floor plan) and (b) steel-profile donor structure (axonometric drawing).

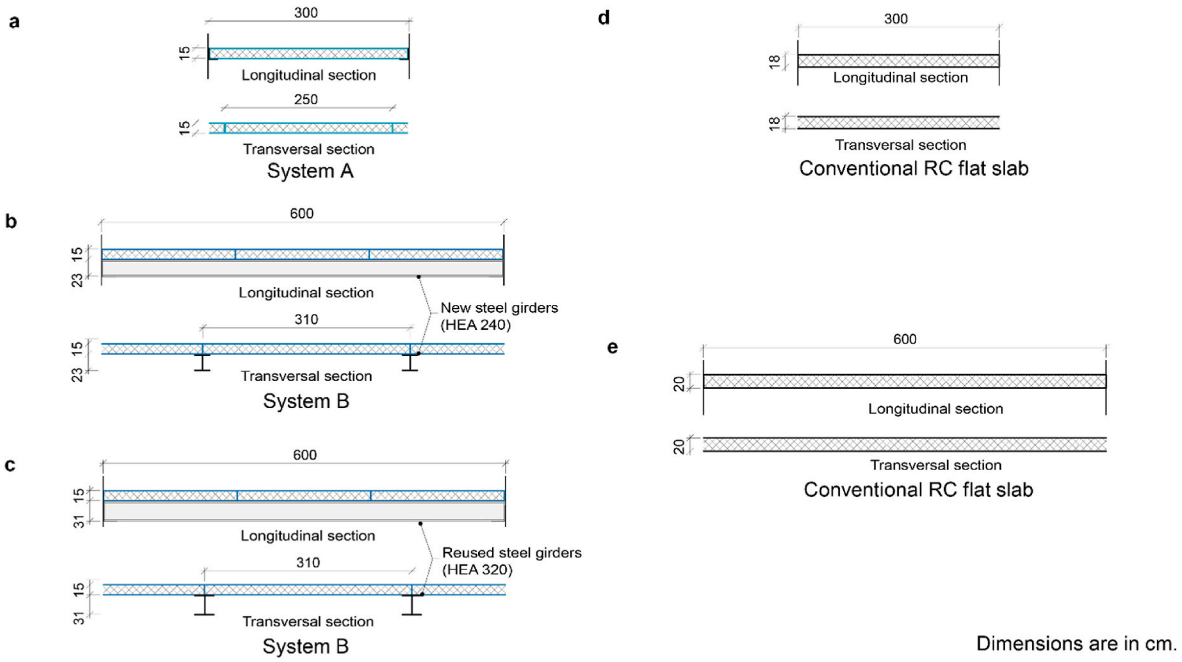


Fig. 17. The case-study design solutions for new floors: (a) 3-m reused RC floor; (b–c) 6-m reused RC floor with new and reused steel girders, respectively; (d–e) 3-m and 6-m new RC flat slabs.

Table 2
Global warming potential of the case-study floors.

Span [m]	Floor type		GWP [kgCO$_2$e/m^2]
3	Conventional RC flat slab		67
	Reused RC floor (System A)		11
6	Conventional RC flat slab		74
	Reused RC floor (System B)	with new steel girders	22
		with reused steel girders	9

girders also drastically decreases greenhouse gas emissions (Fig. 18b). When combining reused cut RC pieces with reused steel girders, GWP is cut by 88 % compared to a conventional RC flat slab. When, instead, newly-manufactured steel girders support the cut RC pieces, reductions lower to 71 %.

Compared to the production of 1′000 m^2 of a conventional RC 20-cm flat slab, creating 6m-long spans with reused slabs and steel girders (Fig. 18b) avoids emitting between 52 and 65 tons of CO$_2$e depending on whether the girders are reused or not. Moreover, the production of 454 tons of concrete is avoided, and 375 tons of reinforced concrete are directly reused and diverted from the elimination route. The difference in GWP between the reused floors built with new or reused steel girders is due to the emissions caused by the production of the new steel profiles, which accounts for 66 % of GWP of the concerned floor. For the reused-RC floor combined with reused steel girders, 81 % of GWP is caused by the production of new material production, 2 % for the cut RC piece sawing, 10% for their transportation, and 6 % for other processes separately accounting for less than 1%. Overall, these results confirm the drastic GWP, natural-resource use, and waste reductions provided when reusing old RC slabs as-is in new buildings.

4. Discussion

4.1. Relevance

The new floor systems presented in this paper are holistic answers to simultaneously reduce several urgent environmental issues related to the construction industry: waste generation, natural resource extraction, and greenhouse gas emissions. A main and original dimension of the work is that the new floor systems reuse all pre-existing structural capacities of CIP RC slabs, counting on both the tensile strength of the steel

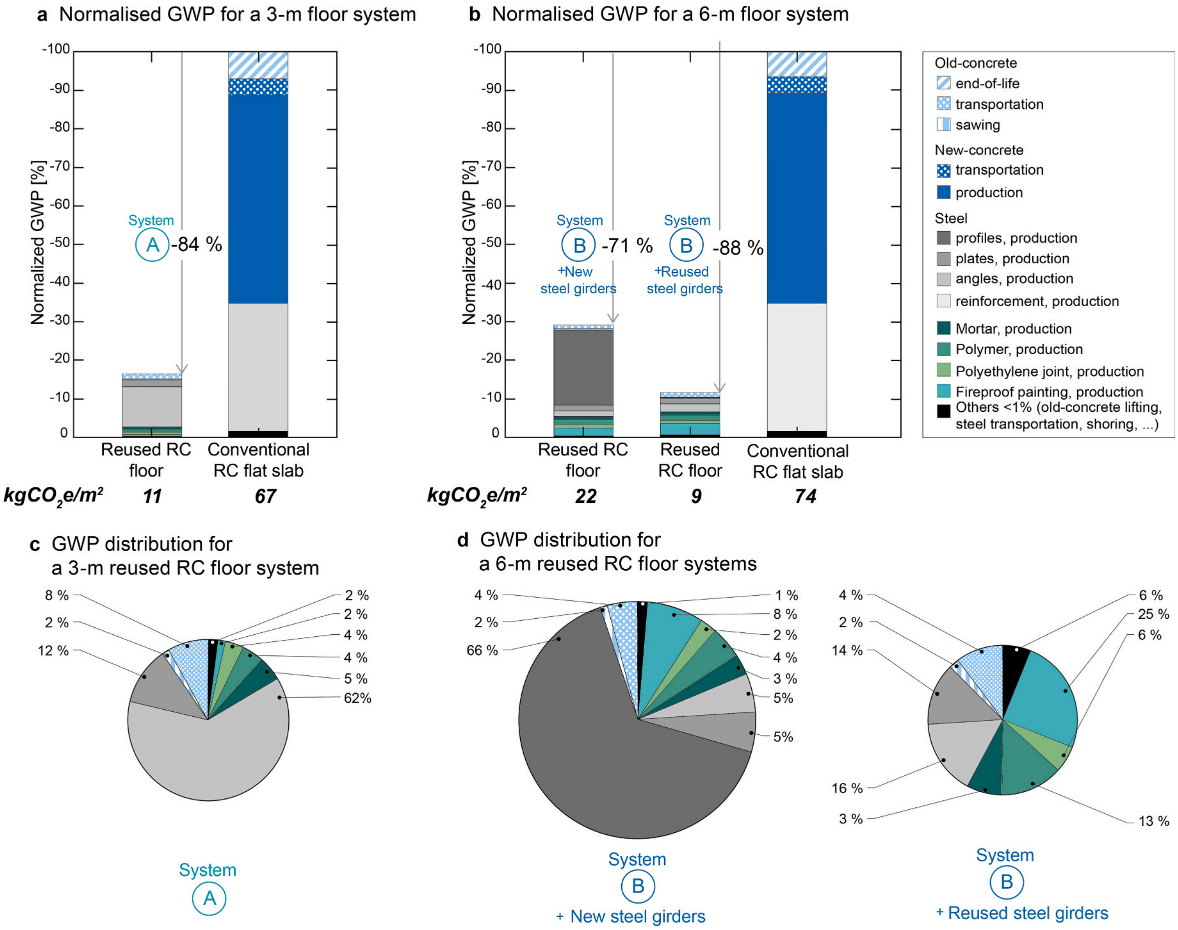


Fig. 18. Global warming potential of 3-m and 6-m spanning floor designed for the case study. Pie-chart circle areas are proportionate to total GWP.

reinforcement bars and the compressive strength of concrete. Reusing CIP RC in bending re-utilises the structural properties of RC more than when reused under compression only, which was the approach used in previous research projects resuing CIP RC such as the Re:Crete arch footbridge designed by Devènes et al. (2022). Thus, the new systems and the original design procedure support a highly efficient and circular re-utilisation and management of existing resources, which is recognised as a key pathway toward sustainability by the European Commission (2020) and the International Energy Agency (2019). The valorisation of existing characteristics is also present in that the new floor systems benefit from the discarded-concrete existing acoustic and fire performance. Nevertheless, future work should further investigate how acoustic and fire performance meet current standards for new construction.

The environmental assessment results obtained for the new floor systems corroborate the significant reductions reported in the literature for other RC reuse designs and previously reviewed by Küpfer et al. (2023). With an average GWP reduction of 80 % compared to conventional design and an average GWP of 15 $kgCO_2e/m^2$, the reused-concrete systems are exceptionally low carbon floor systems. This result is even more significant when combining reused RC with reused steel, which leads to GWPs as low as 5 $kgCO_2e/m^2$ and consistently below 17 $kgCO_2e/m^2$. To the authors' knowledge, the proposed systems set a radical sustainability benchmark in concrete floor construction. While acknowledging the differences between studies regarding structural layout and design and/or LCA modelling, reused-concrete floor systems offer a new, ultra-low-carbon solution among other concrete floor solutions. For example, Jayasinghe et al. (2022a) quantified the GWP of a large set of market-ready designs on columns, including post-tensioned flat slabs and hollow-core slabs. The lowest GWP for spans between 4 and 8 m ranges between 68 and 87 $kgCO_2e/m^2$, and is obtained with flat two-way slabs on beams. Regarding novel optimized systems, Agustì-Juan and Habert (2017) computed the climate change potential of a 2.8-m long optimized rib-stiffened funicular floor system developed at ETHZ (López et al., 2014) and reported an environmental impact of approximately 46 $kgCO_2e/m^2$. Later, Ranaudo et al. (2021) documented the construction of another variant of concrete rib-stiffened funicular floor and reported a GWP of 29 $kgCO_2e/m^2$. Oval et al. (2023) developed a segmented concrete shell floor prototype on columns, with GWP ranging between 29 and 46 $kgCO_2e/m^2$ for spans between 4 and 8 m (Jayasinghe et al., 2022b). It should be noted that these systems are supported by columns, whereas the systems proposed in this study are supported by walls, and would require slight adaptations for an accurate comparison. A proper comparison of the pros, cons, and limitations of reusing concrete slabs and other novel and market-ready solutions is the topic of a separate research project.

The case study in this paper demonstrates the applicability of the design procedure to a selected couple of full-scale donor buildings. To make the design procedure more accessible and user-friendly, a web application has been developed (https://flore.epfl.ch). The user enters the donor and receiver building characteristics, and the web application recommends a preliminary design solution, and informs the user of the estimated upfront greenhouse gas emissions of the solution. Up to three donor and receiver building combinations can be simulated simultaneously.

4.2. Limitations and future work

The study is limited to reusing slabs in good condition in new buildings. The details are designed to protect cut steel reinforcement bars from corrosion. As for any concrete structure, the envelope of the building is essential to protect the structure from water exposure and thus prevent new- or reused-concrete degradation. When buildings are properly designed and concrete is protected from exposure to water, concrete carbonation occurs at a very slow pace and does not normally threaten the structural performance of slabs. Moreover, non-structural elements such as painting, screed or flooring may reduce the carbonation speed as concrete will not be directly exposed. Overall, the new systems are designed for the same expected service duration as new RC slabs. Nonetheless, the assumptions on the RC condition made at the preliminary design stage must be validated later on in the process through visual inspection and non-destructive/destructive methods (Devènes et al., 2024). Moreover, the durability of the new systems should be further investigated in future work, e.g. by adapting the degradation model predictions for reused concrete bridge girders proposed by Xia et al. (2022).

The study is also limited to the preliminary design phase, with material property hypotheses based mainly on old standards. In the following project phases, hypotheses on existing structural characteristics must be further confirmed, typically using engineering drawings and testing campaigns. Further investigations of the structural behaviour of reused concrete should be conducted to support comprehensive design guidelines. Large-scale slab testing is thus under planning, and a full-scale prototype is under construction.

Another limitation of the design options is that the study explores only the reuse of unidirectional slabs. If considering the reuse of bi-direction slabs, the allowable cut RC span must be readjusted according to the bending moment used to calculate the resistance of the donor slabs (Equation (1)). However, the resistance provided by minimum reinforcement $M_{Rd,a,m}$ would remain the same since assumptions on minimum reinforcement would be similar. Since the span allowed by the resistance $M_{Rd,a,m}$ is often between 3.5 and 5 m, the results when reusing short- and mi-span bi-directional slabs are broadly expected to remain comparable. In addition, the study is limited to slabs passively reinforced with ribbed rebars, which may not be the case in countries other than Switzerland.

The numerical results of this study are linked to old and existing Swiss norms, and the case study is also located in Switzerland. Numerical results may vary when applying the procedure to other construction basins where past or existing norms differ. Future work could include testing the procedure and the result sensibility on case studies in different construction basins.

The receiver-system influence on building design is another matter of discussion. In system B, the steel girders imply a larger floor thickness than a new flat RC slab. However, girders may be integrated within a technical suspended ceiling, as commonly used in office buildings. Other types of girders could be studied to reduce the total floor height in System B. Regarding the sub-surface of the cut RC concrete, every project will have a unique surface and piece pattern and generate new aesthetic options. However, it is left to the choice of the designer to cover it or leave it visible. In general, construction detailing may be adjusted based on local construction customs and other architectural considerations. Overall, a multi-criteria analysis using an extended set of analysis criteria with aspects such as costs, construction ease, or design implications, would support a more comprehensive assessment of the new systems in the future (Küpfer et al., 2021). A cost analysis is planned for future work.

Because the study focuses on global warming potential and concrete waste masses, the assessment is limited to two environmental indicators, but future work could extend the set of environmental indicators. In addition, the study is limited to the intrinsic limitations of LCA, notably its linear model equations. This feature limits the sensitivity of the results to economies of scale, which should be explored in future work. Regarding the quality of the data used in the study, impact factors mostly come from widely used and recognised databases (Ecoinvent, 2019; KBOB, eco-bau & IBP, 2022, 2023). However, some factors have been calculated by combining small on-site measurement samples and industry information. These less robust sources add to the uncertainty of the results, but the analysis (Sections 3.2.3 and 3.2.4) shows that results are not sensitive to them.

The industrial (technical and logistical) context necessary for broadly implementing the developed floor systems is customary in developed countries. The new floor systems are primarily built from one of the largest waste streams – discarded RC – and require machinery and techniques commonly used by RC sawing companies, prefabricated RC companies, and engineering offices that maintain existing structures. Nevertheless, a condition is to overcome the prevalence of demolition activities over careful deconstruction and synchronisation challenges between the donor and the new structures. Other general constraints regarding the industrial large-scale adoption of RC reuse have been identified by Küpfer et al. (2023), including the need for new liability schemes and additional built precedents reusing CIP RC in bending. In parallel, optimising the cut piece dimensions, simplifying the construction process, and using only standard tools are expected to keep the construction costs low and balance the extra sawing costs. Still, economic viability should be further assessed in future work.

Although reusing concrete slabs offers unprecedented environmental benefits when considering a new building construction, its generalisation across the entire construction industry is bounded. Indeed, in Switzerland, for instance, 12.67 km^2 of new building floors are constructed yearly, whereas 1.78 km^2 of building floors are demolished yearly, on average, between 2000 and 2020 (Federal Statistical Office, 2020). This means that if all demolished floor areas were idealistically reused to replace newly built floor areas, reusing slabs would replace 1/7th of the annual production of new floors in the country. While this ratio's upper bound may seem small, reaching it would bring environmental benefits not achievable by other construction-related manufacturing and recycling strategies. Besides, the only environmentally viable way to modify this ratio is to reduce demolition and construction activities themselves.

5. Conclusion

This paper extends the field of possibilities for designing with reused components. It introduces two new floor systems that respond to an urgent need to reduce the detrimental environmental impacts of load-bearing floor construction by reusing saw-cut reinforced concrete (RC) pieces salvaged from soon-to-be demolished structures. The new floor systems stem from the untapped idea to efficiently prolong the use of discarded cast-in-place (CIP) RC slabs, reusing their existing structural features at full capacity, particularly their bending resistance. The systems' main limitation lies in their scalability since procurement is limited to the flow of discarded RC structures. As part of the preliminary design process, the paper provides a procedure to estimate the maximum span of RC pieces to be reused in bending in the new systems. The systems' design potential and environmental benefits are tested with the parametric design of 20′280 combinations of donor and receiver structures in Switzerland and their environmental analysis through Life-Cycle Assessment. The main findings are the following:

- Existing structural capacities allow pieces cut from continuous CIP RC slabs to be reused as simply-supported slabs without strengthening when they do not exceed a specific span. This span can be calculated at the preliminary design stage using the piece geometry and design assumptions from existing structure standards. The lower bound of this allowable span is 3.2 or 4.1 m for a 14- or 18-cm thick donor slab, respectively. This is specific to Switzerland and remains to be calculated for other geographical applications. During further project phases, design assumptions must be verified through material and structural testing.

- The new floor systems have ultra low detrimental environmental impacts, with a reduction of upfront greenhouse gas emissions averaging 80 % compared to conventional practice and solutions as low as 5 $kgCO_2e/m^2$. For 4-m spanning floors, the average GWP is 13 $kgCO_2e/m^2$, with values ranging between 5 and 23 $kgCO_2e/m^2$. When transporting the reused components over 100 km, GWP reductions average 76 %. Reductions reach up to 94 % when reused cut RC pieces are combined with reused steel girders. Future work will expand the comparison to other criteria, including costs.
- A case study designed with elements extracted from existing Swiss buildings confirms substantial reductions in GWP through a refined LCA. When cut RC pieces are reused as primary elements in 3-m-span floors, GWP reductions reach 84 %. When reused as secondary elements in 6-m-span floors, GWP reductions reach 71 % if combined with new steel girders and 88 % with reused ones.

Overall, the findings call for reconsidering soon-to-be demolished RC structures as valuable construction component mines with immediate relevance. The development of comprehensive design guidelines for concrete reuse, the demonstration of the system's feasibility and performance through the construction and testing of a full-scale prototype, and an in-depth analysis of demolition activities are future research priorities.

CRediT authorship contribution statement

Célia Küpfer: Conceptualization, Formal analysis, Funding acquisition, Investigation, Methodology, Software, Validation, Visualization, Writing – original draft. **Numa Bertola:** Conceptualization, Funding acquisition, Investigation, Methodology, Software, Writing – review & editing. **Corentin Fivet:** Conceptualization, Funding acquisition, Supervision, Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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Appendix

Stage	Unit	$kgCO_2e/unit$	Source
End-of-life			
Concrete elimination	kg	0,013	KBOB, eco-bau & IBP (2022)
Steel reinforcement elimination	kg	0,009	KBOB, eco-bau & IBP (2022, 2023)
Shoring	m^2	4,0E-04	KBOB, eco-bau & IBP (2022); industry, and sample measurements
Concrete sawing	m^2	0,729	Devènes et al. (2022); KBOB, eco-bau & IBP (2022); ADEME (2022); industry and sample measurements
Steel unwelding	m	0,163	Brütting et al. (2020)
Lifting	kg	6,2E-05	KBOB, eco-bau & IBP (2022); industry
Material production			
Steel girder/plate/bolt production	kg	0,731	KBOB, eco-bau & IBP (2022)
Fire-proof coating production	m^2	4,390	KBOB, eco-bau & IBP (2022)
Mortar production	kg	0,393	KBOB, eco-bau & IBP (2022)
Polyethylene foam production	kg	1,530	KBOB, eco-bau & IBP (2022)
Formwork production	kg	0,415	(KBOB, eco-bau & IBP, 2022)
Polymer production	kg	2,740	KBOB, eco-bau & IBP (2022)
Concrete production	kg	0,089	KBOB, eco-bau & IBP (2022)
Steel reinforcement production	kg	1,125	KBOB, eco-bau & IBP (2022, 2023)
Steel sandblasting	m^2	0,054	Brütting et al. (2020)
Steel welding	m	0,163	Brütting et al. (2020)
Steel degreasing	m^2	7,9E-03	Brütting et al. (2020)
Construction process			
Lifting	kg	6,2E-05	KBOB, eco-bau & IBP (2022); industry
Concrete pomping	m^3	1,000	Oekobaudat (2021)
Transport			
Transport by truck	tkm	0,118	KBOB, eco-bau & IBP (2022)

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