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Reusability assessment of reinforced concrete components prior to deconstruction from obsolete buildings

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ABSTRACT

A large part of building demolitions is motivated by purely socio-economic reasons. Hence, about-to-be-demolished structures, commonly made of reinforced concrete, very often present no or little degradation. When adaptive reuse of the entire building is not possible anymore, its deconstruction and the reuse of its load-bearing components elsewhere in new structures maximize the reclamation of preexisting structural qualities. This strategy drastically decreases the environmental burden of both demolition and subsequent new construction. However, its efficient implementation requires a careful preliminary assessment of the existing structure, including the inventory of its components, and the evaluation of their reuse potential in relation with their preexisting damages and possible future uses. Currently available procedures are not exhaustive and focus solely on precast components. This paper thus introduces a specific methodology for the reusability assessment of load-bearing reinforced concrete components, focusing in priority on their long-term durability. It first proposes a systematic protocol to classify and quantify the components, investigate their geometrical and material properties and evaluate their preexisting damages. Then, the paper develops a new procedure to grade the reusability of the components for future projects. Finally, the whole methodology is tested on three case studies in Switzerland, demonstrating its robustness and repeatability. In these three case studies, 95 % of reinforced concrete components are graded as reusable.

1. Introduction

1.1. Context

Mainstream since the 1950s in developed countries, reinforced concrete (RC) is the most ubiquitous material in building structures worldwide. Concrete has many qualities, including competitive mechanical and fire resistance, versatility, accessibility, and economic viability. However, its production requires cement, gravel, sand, and water, leading to large detrimental environmental impacts (DEI). Cement production alone is accountable for 9 % of all worldwide process-related greenhouse gas emissions [1]. Moreover, a shortage of raw materials needed for concrete and cement production – i.e., sand, gravel, limestone – is expected shortly due to the limited extraction possibilities [2]. Concrete production also accounts for approximately 2 % of global water withdrawal [3]. Regardless of these critical embodied impacts – i.e., impacts due to the production, construction, transformation, and demolition of buildings – existing buildings made of RC are frequently demolished for non-technical reasons to make place for new buildings in adequation with current programmatic or real-estate investment needs [4,5]. Consequently, concrete represents about a third of Euro-

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pean construction and demolition waste [6]. Therefore, there is a need to reduce the DEI of concrete construction while at the same time reducing concrete demolition waste.

Several strategies exist today to reduce CO_2 emissions from the cement and concrete industry [7]. They can be applied to various stages of the cement and concrete manufacturing, design, or disposal processes. It includes, but not exclusively, the use of alternative materials or fuels for cement production, the substitution of clinker for other substances, optimization of concrete, mixes, and structural design efficiency [8]. On the other end of the design process, the circular economy principles aim to extend the existing product lifespan. Applied to concrete construction, they suggest, in order of priority: (1) using the existing structure with little to no transformation, (2) renovating, transforming, and strengthening the existing structure, (3) deconstructing and reusing the load-bearing components and their intrinsic qualities in new assemblies, (4) recycling by crushing the existing concrete and using it to replace up to 40 % of natural gravel in concrete mixes [9]. The latter reduces the DEI linked to gravel extraction as well as the amount of waste. However, it does not reduce the need for cement and the related CO_2 emissions [10].

1.2. Scope

While all the above-mentioned traditional and circular strategies are necessary and complementary to effectively reduce the DEI of concrete construction, component reuse (third strategy) is the least developed one. It consists in carefully dismantling the components of an obsolete structure – i.e., the *donor* structure – to reassemble them into a new structure – i.e., the *receiving* structure. By extending the component's use in its initial or a similar function, it is possible to simultaneously reduce the amount of waste, greenhouse gas emissions, and the demand for new raw materials. Precedents of concrete component reuse have been identified since the 1980s by Küpfer et al. [11]. Most relate to the deconstruction and reassembly of prefabricated RC panels from mass-housing buildings in Germany, the Netherlands, Finland, and Sweden [12–14]. Fewer projects have reused components saw cut from obsolete cast-in-place RC structures using diamond saw blades. Notably, large frames have been reused to construct pavillions and housing prototypes [15,16]. A 10-m arch footbridge prototype, shown in Fig. 1, has also been built by assembling and post-tensioning 25 blocks saw-cut from the walls and foundations of a building [17].

As previously identified by Gorgolewski [18], load-bearing component reuse involves changes in the design process of the project. Recently built projects have used two main approaches to integrate reclaimed RC structural components in the design process. In the first approach, stocks of available RC components are identified once the concept and preliminary design of the new project are set. It is then expected that the stock and the project's needs match as much as possible. In the second approach, the concept and preliminary design of the new project are based on assumptions made about the properties of a previously-identified donor structure. These two approaches require high flexibility in the new project design because it might lead to significant modifications during the detailed design stage, i.e., once information on the available stock of RC components or the project's requirements gets more detailed. In the worst case, incompatibility of demand and offer might lead to abandoning the reuse objective.

To prevent this pitfall, a proper early identification and audit of the obsolete structure(s) is crucial [18,19]. This paper thus develops a specific and systematic procedure for this audit and the following reusability assessment of the obsolete RC structure, focusing in priority on the durability of reused RC components. This procedure is central to the whole reuse strategy. It includes the classification and inventory of components, their damage and qualitative assessment, and the evaluation of their reusability. It concentrates on the component reuse strategy of existing RC structures which are considered as an assembly of pieces that can be dismantled. Adaptive reuse – i.e. the reuse of the whole structure, through rehabilitation and transformation – is out of scope.

1.3. Paper organization

This paper is divided as follows. Section 2 introduces the reuse of construction components as well as state-of-the-art methods for assessments of existing structures and stocks for reuse. It also highlights the identified research gaps. Section 3 presents the objectives and methodology of the paper. The reuse-driven project phases and how the reusability assessment integrates with them are introduced in Section 4. Section 5 details the protocol to audit an obsolete structure while aiming at promoting the reuse of its components. It includes a method to evaluate preexisting damages on RC components. The steps for the reusability grading of a donor RC structure are detailed in Section 6, based on three criteria: damage, use, and intervention. Three case studies are presented in Section 7 to validate the results. Finally, Section 8 discusses the results and future works before Section 9 concludes the paper.

Fig. 1. Footbridge prototype [17]: (a) sawing the blocks, (b) storage of the blocks, and (c) final 10-m arch prototype.

2. State-of-the-art

2.1. Reuse of construction components

Considered common sense prior to industrialization, the reuse of construction components lost its interest with the mechanization of construction sites and the rise of labor costs [20,21]. The strategy is nowadays a niche practice, and most recent projects concern the reuse of indoor components or furniture, such as flooring, kitchen furniture, or sanitary equipment [21,22]. However, a few notable examples of building projects involving the reuse of envelope or structural components were built in the last two decades. For instance, *La Cuisine* of the Winnipeg Folk Festival in Birds Hill Park, Canada [23], and the heightening of the *Halle 118* in Winterthur, Switzerland [24] reused steel load-bearing structures and facade panels. In the early 2000s, various projects reused prefabricated RC components deconstructed from large mass housing buildings in northern Europe [11,14]. Among others, the Nya Udden apartment project in Linköping, Sweden, reused 400 components (walls, beams, and staircases) to build 54 flats [25]. In Germany, panels (walls and slabs) were reused to build 1- to 2-floor buildings: garages, single- and multi-family houses, and association houses [12,13]. Similarly, garages and garden pavilions were built with reclaimed walls and slab panels in Raahe, Finland [14].

Researchers have identified barriers to reusing load-bearing components in the construction industry [11,18,26,27], mainly:

1. Economic constraints. Costs for reusing structural components in projects only minimally vary from conventional procurement methods, with profitable and unprofitable examples [11,28]. Moreover, profitability is expected to improve with the mainstreaming of the practice and the increase of landfill taxes, energy, and new material prices [28].
2. Inadequate construction and demolition methods. The construction and demolition methods commonly used today are not well adapted to reuse. Most existing buildings were not built reversibly [29], which leads to demolition followed by recycling or landfilling of the materials. Instead, selective deconstruction or reverse logistics promotes the reuse of construction component at the end of the donor structure use cycle, by dismantling carefully and making the components available for a new use in the receiving building [30,31].
3. Modified project phases. The design of a reuse project is constrained by the available stock of components [32] and must adapt to variability when, in the early phases of the project, the precise stock composition of reusable components is still unknown [18]. This might lead to additional iterations in the design.
4. Complex supply chain logistics. The supply process of a reuse project consists in synchronizing the dismantling with the reassembling of components, sometimes with a storage phase in between. With the inexistence of a reseller market for reclaimed structural components, logistical efforts are required by both the donor and the receiving projects, which may lead to delays and costs if not well managed [18,27,28].
5. Lack of technical guidance. New standards are required to guide the design and planning of reuse projects. These should include assessment methods of obsolete structures and reconstruction details [11,27].
6. Additional performance assessment and certification. The material properties of the reclaimed components must be verified, and the structural performance assessed by testing and calculation [18,26]. Protocols to verify the geometric and material properties of existing components in view of their reuse have been proposed for steel [33–35] and timber [36]. However, methods available to assess existing structures (see Section 2.3) still need to be adapted to the specificities of RC component reuse [11].

Early in the deconstruction project, a precise and organized knowledge of the quantity, as well as the geometrical and mechanical characteristics of the components must be acquired [18,19]. This would allow leveraging several identified barriers by notably simplifying the project phases (barrier 3) and allowing better deconstruction planning and synchronization with the receiving project (barriers 2 and 4). Reuse operations are indeed eased when coherent information is available to the different stakeholders – e.g., resellers, project owners, engineers, architects, and demolition companies – early in the project development. The collected information should be obtained through procedures specific to the structural material (barriers 5 and 6).

2.2. Reclamation audits for reuse

Currently, the reuse of construction components is often already managed with reclamation audits. Components of the audited building are considered reusable if they can be easily dismounted, transported, and stored while presenting a residual market price [37]. The current practice mainly concerns non-structural components such as flooring, doors, windows, technical equipment, or simple structural elements such as bricks, timber, or steel beams [38]. The audits aim to inventory potentially reusable components in soon-to-be-demolished or transformed buildings without focusing on one specific component type. The document helps to plan the selective deconstruction of the building and the reuse of its components. The audits' exhaustivity and quality largely depend on the authors' expertise.

Few examples of standard reclamation audit protocols exist, most of which are reviewed in a report by the European research project "Facilitating the circulation of reclaimed building elements in Northwestern Europe" (FCRBE) [39]. The earliest procedure was proposed in 2003 in Florida, USA, inside a guide on deconstruction processes [40]. In Europe, the Belgium design office Rotor developed a guide on the off-site reuse of construction components [37], including an audit method. In both documents, the protocol is simple and straightforward. The audits are done by construction professionals during on-site visits. The selected components are inventoried in a table including photos, quantities, dimensions, weight, type, initial production date, location in the building, and estimated value.

In France, as part of the research project REPAR #2 [41], Bellastock, a French architecture office, also developed a reclamation audit protocol for buildings. They propose to collect and synthesize data about a given component stock on detailed factsheets, including accessibility of the components, eligibility to reuse, and any relevant technical information that might be acquired through specific investigations. They include concrete elements and propose different reuse cases, both structural and non-structural.

Finally, the FCRBE project delivered guidelines for reclamation audits [38] based on the previous work by Rotor, Bellastock, and other European reuse experts. It proposes to summarize the information of the different identified elements in a table containing primary information completed in specific factsheets for each listed element. The factsheets give information on context, assembly, toxicity, environmental benefits, and potential reuse application.

Four procedures to assess the reusability of reclaimed RC components are known to the authors. The first one was developed by a Brandenburgische Technische Universität Cottbus (BTU) research team for the state of Brandenburg, in Germany. It is a short technical memorandum on the reuse of precast RC panels [42] in which they propose four verification phases to check the validity for reuse of a precast RC component: preliminary, suitability, main, and additional phases. The goal is to verify if the components conform to in-force design codes and are fit for dismantling and reassembly. The preliminary phase consists in reviewing all existing data on the existing structure. A visual inspection of the components in place in the existing structure, and material and structural testing are carried out for the suitability phase. The results of this phase are used to grade the reuse potential of the components according to a simple 4-level scale. The main and additional phase consists of visually examining the elements again after their dismantling, transport, handling, and storage. This procedure lists for the first time the different verifications required to assess the reuse potential of an RC component.

The second published procedure to assess the reusability of RC components was developed in Norway and focused on prefabricated hollow-core slabs [43]. This national standard goes through the steps required to assess the reclaimed hollow core slabs, similarly required for newly factory-produced ones. It recommends the study of existing documentation and a condition and structural assessment based on visual inspection and material testing. The load-bearing capacity is verified through a full-scale load test. The standard ends with a checklist for the different project phases (inventory, deconstruction, transport, storage, and reassembly).

The third procedure is developed in the framework of Structural Reuse, a danish research project, and was still in a public draft version for commenting at the time of writing ths paper [44]. The document builds on the above mentioned Norwegian standard for prefabricated hollow-core slabs. Its scope is currently limited to precast elements, with no visible deterioration and constructed after 1969 – date at which standards for precast elements were introduced. It recommends to sort the elements in groups with similar caracteristicus. Each group is then classified into 4 categories, which defines whether the elements of a group are reusable or not and the level testing requirements, from minor to comprehensive. The level of testing depends on the intended use in the receiving structure.

Finally, the fourth procedure is a deliverable for the ReCreate European research project [45]. This project works on the reuse of precast concrete elements, using four real-life projects in Finland, Sweden, Germany and the Netherlands. Their guidelines for a pre-deconstruction audit suggest to use a BIM model to collect and organize all the relevant information on the precast structural elements of a donor building. The final aim is to evaluate if an element is worthwhile to deconstruct for reuse purposes. Recommendations are given on data collection and treatment on the donor building. Visual inspection is used to verify the accuracy and complete the collected data. It also allows to check the general condition of the building and any degradation or damages to the structural elements and is completed with limited destructive and non destructive testing. No specific classification of possible damages or degradations is provided, as this is part of another ongoing workpackage of the research project.

These procedures currently have the following limitations:

› they are limited to the case of precast components;
› no indication is given on how these procedures should integrate into the project phases;
› no detailed inventory method and reporting format is proposed, which might make it difficult for designers to find the required information;
› the simple grading scale proposed in the German procedures does not accurately consider the future use of the reclaimed component, while the other three procedures do not propose any reusability grading.

2.3. *Existing structure assessment*

The condition of an existing structure evolves through time, especially when subjected to climatic variations. It can lead to damages and detrimental anomalies of the load-bearing components, which influence the structure's durability, serviceability, and safety. To overcome the risk of a deficient structural behavior, condition assessments of existing structures are conducted. The most common and straight forward way of assessing the state of an existing load-bearing structure is through visual inspection. Other methods are also possible to make inspection of the built environment less arbitrary and more automated using, e.g., sensor measurement [46], imaging with unmanned aerial vehicle [47], or 3D-scanning combined with virtual reality tools [48].

Nevertheless, visual inspection is a simple, effective, and economical method to quickly estimate the individual damage of the structure's components [49]. It can be performed by any engineer, which therefore also involves a high degree of subjectivity [50] partly erased through standardized methods and protocols. For buildings, most of the procedures based on visual inspection concern the evaluation of facades [51], often the only visible structural components of a building. More detailed procedures exist for bridges for which maintenance is more routinely performed [52–54]. They result in recommendations on the required interventions to insure the good condition of the components and the desired performance capacity. Bertola and Brühwiler [54] describe the component condition as a product of the degradation state and the risk class. As in many other studies, the degradation state is characterized by the extent and severity of the damages [48,50,55]. The risk class is characterized by the consequences of the component failure on the whole structure's safety [50,55].

The visual inspection procedures in the literature are thus mainly intended to maintain existing structures and devise intervention plans. The outcome of these procedures differs from what is expected when assessing the feasibility of reusing RC components. For a new use cycle with a potentially different use, the condition of the components must be good enough to minimize the risks. While the purpose of the condition assessment for future reuse does not include specific interventions, it does consider how they influence the potential for reusing the component by improving its condition.

2.4. Degradation processes of reinforced concrete

As mentioned in the previous section, visual inspection is typically sufficient to identify the most common damages of concrete. These damages have been widely discussed in scientific and engineering publications [56–59]. Table 1 lists the most common RC degradation processes, their causes, how to recognize them through visual inspection, and interventions to repair the damage and stop the process.

Corrosion of steel reinforcement or alkali-silica reaction in concrete are uncommon degradation processes inside buildings, where humidity rates are generally low. In any case, methods are available to determine the chloride concentration, the carbonatation depth, the rebars' related corrosion risk [60], and the presence and progression of alkali-silica reaction in concrete.

Routine damage treatments [59] aim at rehabilitating RC components in their initial function in the structure. However, reclaimed RC components might have a new use and exposition in the receiving structure. Treatments can therefore be scaled accordingly, reduced, or even avoided. RC component treatments are thus influenced by the reuse strategy and inversely.

2.5. Research gaps

The literature review highlights the following four research gaps:

1. The lack of knowledge about the quantity, geometry, and material and structural characteristics of soon-to-be-demolished RC components represents a barrier to planning their future reuse. No complete procedure exists to gather this information for RC components (Section 2.1).
2. Available assessment methods for determining the reuse potential of construction components do not adequately or completely deal with the specificities of RC load-bearing structures (Section 2.2).
3. Available condition assessment methods for existing RC structures do not have the purpose of evaluating the suitability of components for reuse (Section 2.3).
4. Routine damage treatments of RC structures never consider the changes in function, exposition, and geometry of the component, as might be the case for a component reuse strategy (Section 2.4).

This paper aims to fill the above gaps by developing a procedure for the audit and reusability assessment of obsolete RC load-bearing structures, which allows for identifying the reuse potential of the components. The focus is placed on the long-term durability of the reused RC component wich, depending on the intended new use, also impacts its structural safety.

Table 1
RC common degradation processes with their cause, visual signs, and routine treatment [57,59].

Degradation process	Cause	Visual signs	**Routine damage treatment**
Corrosion due to chlorides	Simultaneous presence of oxygen, humidity, and chlorides	Localized corrosion spots on concrete surface; localized spalling of concrete cover; localized corrosion of rebars	Sufficient concrete cover (e.g., additional mortar layer); re-alkalization of concrete; waterproofing (e.g., hydrophobic impregnations, coating, membranes); protection of steel rebars against corrosion (e.g., corrosion inhibitors, cathodic protection)
Corrosion due to carbonation	Simultaneous presence of oxygen, humidity, and de-passivated steel due to carbonation	Concrete spalling over a large area; general corrosion of rebar	
Cracking	Exceptional loads, bad constructive details, restrained deformation, or alkali-silica reaction	Large number of cracks or large crack openings, more than 0.3 mm	Crack bridging with coating to create a waterproof protection; crack injection with resin or mortar to prevent its propagation.
Alkali-silica reaction	Simultaneous presence of reactive aggregates, humidity, and high alkali concentration	Crack mesh at the concrete surface, cracks of slightly brown color	Waterproofing (e.g., hydrophobic impregnations, coating, membranes).
Wet streaks	Circulation of water through the concrete	Wet streaks; efflorescence; limescale stalactites	Waterproofing (e.g., crack bridging, hydrophobic impregnations, coating, membranes).
Spalling	External impact or frost, steel corrosion	Spalling or chipping of the concrete cover without any corrosion of steel reinforcements	Repair spalling or chipping by applying new mortar

3. Objectives and methodology

3.1. Objectives

To fill the gaps listed in Section 2.5, pre-deconstruction tasks are required to acquire the data needed to design with reclaimed RC load-bearing components. The following objectives must be fulfilled: (1) collect all the required data and basic information to characterize the stock and (2) assess the reusability of the structural RC components, with regards to its long-term reusability. This paper proposes a procedure for the reusability assessment that can be applied by any structural engineer while reducing the subjectivity of such assessments as much as possible. The results should be documented in an obsolete structure audit and a reusability assessment report for later use by all project stakeholders – i.e., architects, structural engineers, and others. The procedure is subdivided into four steps, each of which attempts to meet different objectives:

- Inventory of components: How can the components be classified? What are the critical parameters to be aware of regarding the components composing the existing building? How are these determined?
- Damage assessment: Are the RC components still in good condition? What are the essential factors in defining the condition of the components for future reuse? How can the condition of the components be assessed and classified?
- Reusability grading: What factors impact the reusability of RC components? How can a reused RC component be rehabilitated? What difference does it make to reuse RC components rather than rebuilding new ones? How can the proportionality of reusing RC components be evaluated? How can one choose the best way to reuse an RC component?
- Reporting: Can the information be presented in a useful and effective way? How can the quality of a reusability assessment be evaluated?

3.2. Methodology

The reusability assessment procedure proposed in Sections 4, 5, and 6 was developed through an iterative process by analyzing the reuse potential of structural components from three building case studies (BCS), shown in Fig. 2 and presented in Section 7, for which the respective building owners mandated the authors. First, the audit procedures for existing structures were adapted to the specificities of RC component reuse. Then, the fieldwork on the three case studies, which have different contexts, highlighted new questions leading to the adjustment and precision of the procedure. These modifications systematized the procedure and brought more accuracy to the process and results. The reusability assessment results for the different case-studies were then presented to field specialists with a practice of reuse and maintenance of existing structures. For BCS1, the reusability assessment was used in a workshop for planning the reuse of RC components [61]. This workshop provided an opportunity to collect feedback on the procedure, the organization of the results, and, more globally, the component sourcing process regarding the reuse of RC components. Moreover, the case studies allowed the authors to identify some general trends in the reusability of RC elements for structural purposes. This knowledge was used to develop the reusability grading introduced in Section 6.

Although the steps of this procedure were developed in parallel, they are here organized topic-wise:

- Overall design process (Section 4.1) and assessment sequence (Section 4.2);
- Inventory of components, including data collection, classification and quantification of components, and qualitative evaluation (Section 5.2);
- Damage assessment procedure conducted by visual inspection (Section 5.3);
- Reporting and organization of the collected information (Section 5.4);
- Decision-matrix to establish the reuse potential of the load-bearing RC components regarding their durability (Section 6).

4. Reuse project phases

4.1. Adapted design processes

The integration of load-bearing components modifies the processes of both the donor structure's deconstruction project and the receiving structure's construction project. Recent and ongoing projects in Switzerland and Europe [11] that integrate the reuse of

Fig. 2. Building case studies.

load-bearing RC components have shown the emergence of two types of modified project sequences, outlined in Fig. 3(a) and (b). However, despite the success of these pioneering projects, the adopted processes have shown some weaknesses, described hereafter.

Fig. 3(a) illustrates the first type of project sequence. Its characterizing specificity is to identify donor projects after defining the concept and preliminary design of the new receiving structure – see *obsolete structure identification* in Fig. 3(a). With this project sequence, high design flexibility is required with respect to both material and geometrical characteristics of the reclaimed RC components. Once the donor project is identified, the detailed design of the new project is slightly adapted to available components before confirming the feasibility of reuse – see *reusability assessment* in Fig. 3(a). Requirements for extracting the components are defined before the demolition of the source building. This project sequence requires a good knowledge of the existing building stock and a good prediction of soon-available components. Alternatively, it requests a structure typology whose geometry is little constrained by the geometry and mechanical properties of the reclaimed components. This is the case when reusing smaller elements for instance, as showcased by the following three projects recently built in Switzerland: the Re:Crete footbridge, a post-tensioned segmented arch bridge made of 25 reused concrete blocks [17], the indoor and outdoor carriageable pavements made of saw-cut RC elements reclaimed from several transformation and demolition sites [62], and a project integrating reused RC blocks to build column foundations [63].

Fig. 3(b) illustrates the second type of project sequence. In this case, the concept of the new receiving structure is developed after identifying the donor structure – see *obsolete structure identification* in Fig. 3(b) – but before any assessment is done on the obsolete structure – see *reusability assessment* in Fig. 3(b). Preliminary design is based on assumptions directly made from known donor structure properties and capacities, which requires a good knowledge of historic construction techniques. As the donor structure is identified before the conceptualization of the new structure, this sequence favors the reuse of larger components, or even whole structural modules, made of an assembly of components. For instance, this is the case for a project in the Netherlands were large box-like pieces – two side walls, top and bottom slabs – were extracted from a multi-family housing building and reused to build the load bearing structure of a small exhibition pavillon and house prototypes [15,16].

In both project sequences presented above, the late characterization of the donor structure and the late reusability assessment can lead to heavy, late, and costly project modifications during the detailed design stage and might result in abandoning the option of reusing concrete components in favor of new materials. The presented projects also show that the practice has not yet established a definitive process specific to reuse projects.

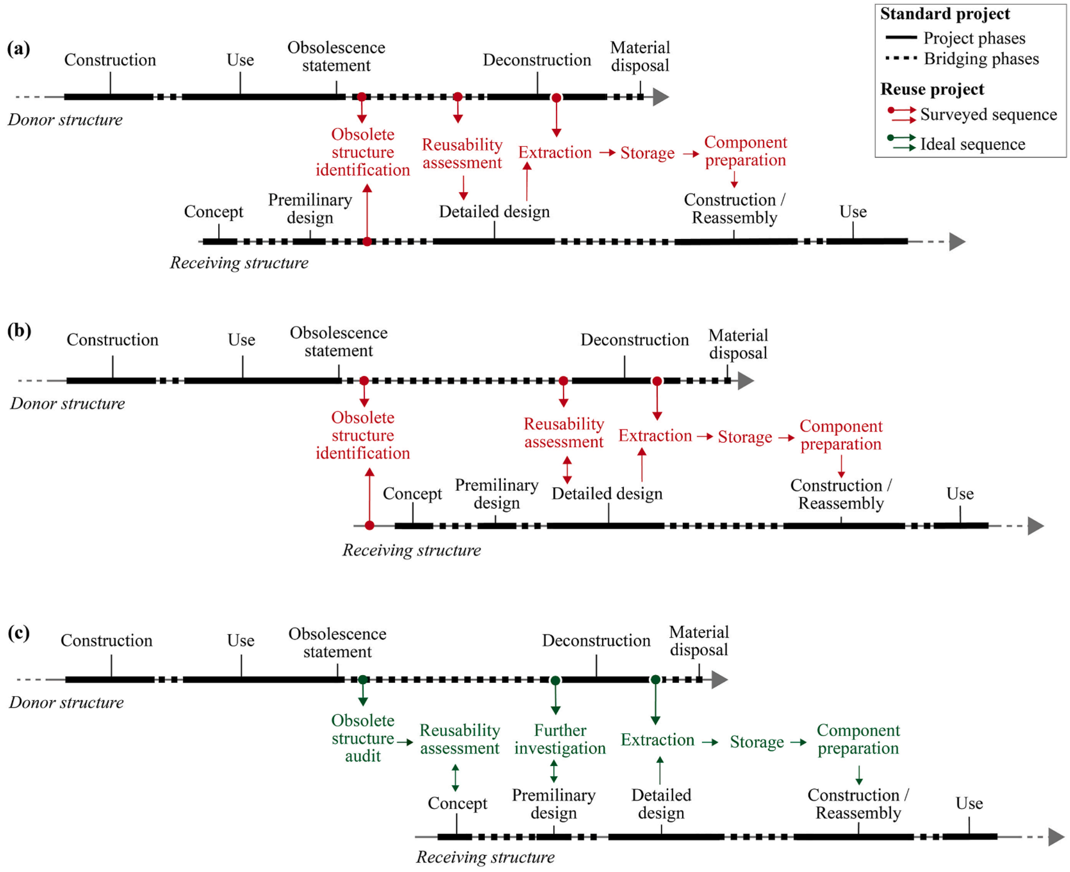


Fig. 3. Reuse project phases: (a) Early prediction of material availability; (b) Early identification of obsolete structure; (c) Early assessment of obsolete structure.

Consequently, Fig. 3(c) illustrates an ideal integration of phases specific to reuse in which an *obsolete structure audit* followed by a *reusability assessment* of the donor structure(s) are established before and during the conceptual design of the receiving structure(s). The audit consists in inventorying the obsolete structure's components and evaluating their properties. The collected information facilitates the integration of reclaimed RC components in the design of the receiving structure. The reuse potential of the components in the new receiving structure is then evaluated. It depends on the proposed concepts and the resulting use case for the reclaimed components. Iterations between the reusability assessments and the conceptual design phases are likely. Further stock investigations might be required to validate the chosen solution, which can be realized during the preliminary design phase of the receiving structure.

4.2. *Obsolete structure audit and reusability assessment*

Fig. 4 further details the *obsolete structure audit* and the *reusability assessment* steps. The first one, framed in red in Fig. 4 and developed in Section 5, focuses only on the obsolete structure and is realized right after the obsolescence statement. Highlighted in grey in Fig. 4, the *input* of the audit is all available data on the donor building. The steps for the complete audit of an obsolete RC structure and its components include the inventory of components, the damage assessment, and a first report. All the collected data is organized in this audit report, the first *output*, highlighted in green in Fig. 4, and information on each component type is summarized in factsheets. The authors recently made available a template for these factsheets [64].

The *reusability assessment* of the RC components integrates demands originating from the receiving structure concept. Four technical requirements influence the assessment:

1. The *durability* of RC, which is greatly impacted by the climatic environment;
2. The *structural capacity,* which is characterized by concrete and reinforcing steel characteristics;
3. The *constructive detailing* and adaptation to actual standards;
4. The *logistics* related to deconstruction, sawing, storage, and transport capacities.

The assessment of component reusability regarding their durability is influenced by preexisting damages evaluated during the obsolete structure audit. One method for establishing the assessment, the *reusability grading*, is presented in Section 6 and framed in green in Fig. 4. The reusability grading is assumed to be independent of the components' quantity in the donor structure. However, whether the donor structure can provide sufficient components to build the receiving one and whether there is a need for new material is a further check to perform. All generated information on the reusability assessment is eventually outputted in a second report, highlighted in green in Fig. 4.

5. Obsolete structure audit

5.1. *Purpose*

The obsolete structure audit is meant to collect and organize all quantitative and qualitative information on the donor building necessary to correctly evaluate and plan the future reuse of its RC components. The scope of the proposed protocol is limited to load-

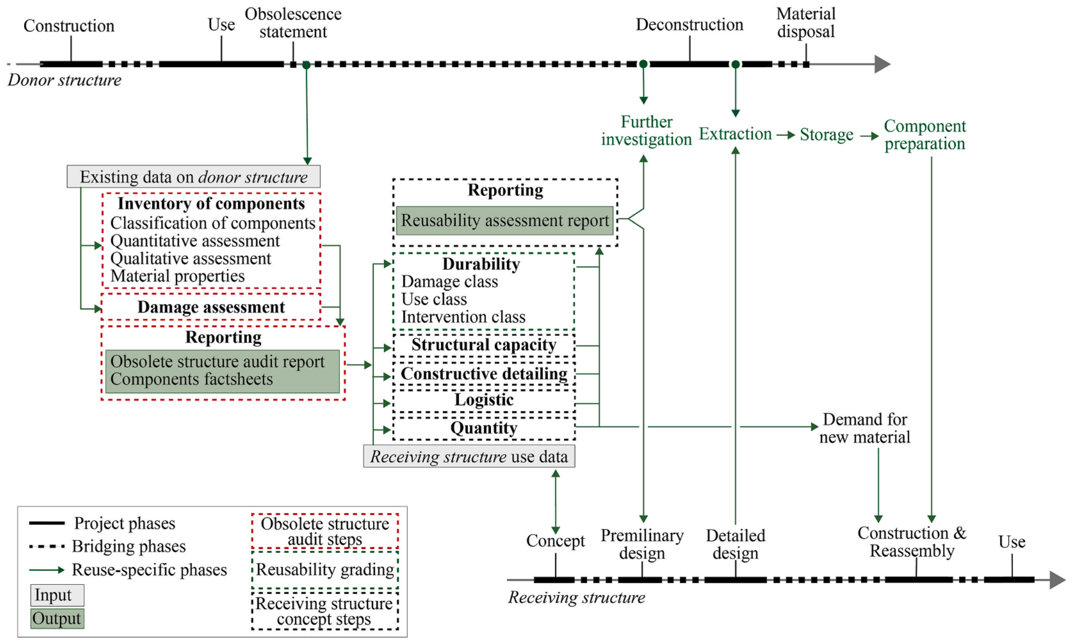


Fig. 4. Flow chart describing the reusability assessment procedure inside the reuse project phases.

bearing RC structures or self-supporting RC components like precast facade panels. In addition, it is expected to remain valid even when a limited quantity of information – i.e., existing documentation, visual inspection, and minimal testing – on the donor structure is known prior to its deconstruction. Therefore, the following assumptions are made:

- Loading history of the component: standard loads for its current and known past use are expected. No exceptional loadings are considered unless damages are visible.
- Deflection of the component: unless obviously visible, the existing deflections due to cracking or long-term effects are expected to be within the standard limits. This assumption should be verified after the deconstruction of the component and before its reuse.
- Deconstruction feasibility: The feasibility of extracting a component from the donor building is not evaluated during the reusability assessment. It is expected to be addressed during the planning of the receiving structure.
- Damages caused during deconstruction: No detrimental damage is expected to occur during the extraction of the building's components. An additional visual inspection should be planned between the deconstruction and the reassembly of the components.

As presented in the following sub-sections, the audit is organized in three steps: the inventory, the damage assessment, and the reporting.

5.2. Inventory of RC components

The inventory of the RC structure components starts with collecting basic data on the donor building – e.g., its location, construction year, use, dimensions, structural system, component geometry, and material properties. Table 2 presents possible but non-exhaustive ways of collecting this data. Existing documentation is the preferred source of information, and its review is the first step of any reusability assessment. It allows the identification of missing information to be collected with other methods. With respect to geometry and material investigations, the number of destructive investigations is preferably kept to a minimum as they are costly and reduce the reuse potential of the components. Non-destructive investigations are conducted to complete the data obtained with other methods and techniques and verify the consistency of the structural and material properties on larger areas without causing further damage to the components.

Based on the collected data, components are classified into categories and types to simplify the assessment. Main categories may relate to the structural function of the RC components – e.g., facades, slabs, walls, beams, columns, and staircases. Then, components with the same characteristics – e.g., material type, construction methods, or assembly – are grouped by types with subtypes for every given dimension. The inventory includes necessary information like dimensions, quantities, and cross-section resistance. It may also include facultative information like the proportional ratio of total structural volume, and embodied environmental impacts.

When no reinforcement drawings are available, assumptions must be made to evaluate the structural capacity of the components, using knowledge of historical construction standards and methods, results of destructive and non-destructive investigations, and structural analysis results on the existing structure. Different levels of approximation can be considered to estimate the structural capacity, each increasing the precision of the assumption:

1. Using minimal reinforcement ratios requirements from the time of construction;
2. Using the resistance demand calculated with the loading requirements from the time of construction;
3. Using the results of combined destructive and non-destructive measurements.

The total volume of concrete of the obsolete structure is obtained during the inventory and used to calculate the volumetric proportions of each component category or type as well as their embodied environmental impacts. These number then allow to identify the component category or type that should be prioritized in the reuse strategy in order to minimize the environmental impacts of the demolition and the receiving structure.

Environmental impacts corresponding to the fabrication process of the RC components and their subsequent demolition and elimination are expressed in terms of global warming potential (in $kgCO_{2eq}$). This indicator is calculated using the weight of the component

Table 2
Data collection.

Method	Techniques	Information
Review of existing documentation	Analysis and data curation from: - Blueprints and drawings - Pollutant diagnostics report - Any other relevant documents – e.g., reports, feasibility studies, public and historical archives, and scientific and technical literature.	Dimensions, rebars layout, material properties, toxic substances presence, construction methods, etc.
Geometry measurements	- Manual measurement - Destructive investigation – e.g., drillings and concrete cover removing - Non-destructive investigation – e.g., control point surveying, geo-radar scanning, 3D scanning	Dimensions, rebar layout, connection details, etc.
Material investigations	- Destructive investigation – e.g., laboratory mechanical testing - Non-destructive investigation – e.g., Schmidt rebound hammer.	Mechanical and durability characteristics, etc.
On-site visits	Visual inspection	Damage and qualitative assessment (color and accessibility).

and equivalent factors available in life cycle analysis databases, such as the one provided by the Swiss authorities [65]. As first approximation, the environmental impacts linked to the steel reinforcement is neglected, but a higher density of 2500 kg/m^3 is considered for reinforced concrete. Transportation from the factory to the construction site is also neglected. The global warming potential of concrete production and elimination is computed by multiplying the weight of the components by respectively 0.089 kgCO$_{2eq}$/kg and 0.013 kgCO$_{2eq}$/kg.

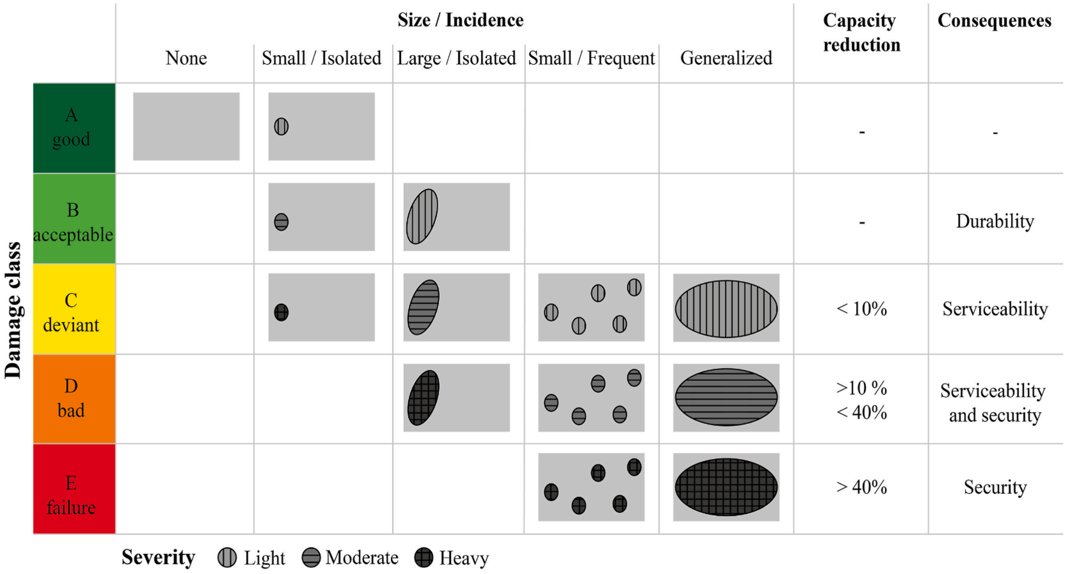
5.3. Damage assessment

Visual inspection is performed on the obsolete structure before its deconstruction. It aims to identify and record the damages of the RC components and, simultaneously, to discard any component type with low reuse potential due to too significant damages that affect their serviceability performance or structural resistance. The damage assessment is the most complex task of the structure audit because damages must be properly interpreted and understood. They are here graded into five *damage classes* by visual inspection, as was also proposed by Bertola and Brühwiler [54] for assessing existing bridge structures. In their work, classes are delimited based on the repercussions of damages and thresholds for reductions in resistance. As illustrated in Fig. 5, it is proposed herein to supplement these thresholds with information regarding the size – i.e., small or large –, incidence – i.e., isolated, frequent, or generalized –and the severity – i.e., light, moderate, or heavy – of the damage. The size and incidence of the damage is evaluated in relation to the overall dimensions of the considered element. The severity of the damage relates to the progression of the degradation process (see Table 1). Ultimately, the incurred damages result in compromised serviceability performance or a reduction in structural resistance of the assessed component.

Components categorized under class A exhibit nearly flawless conditions, whereas those in class B have defects that impact their long-term durability. However, in both classes, the serviceability or resistance of the components remains unaffected. Components in class C have moderate or light damages, yet the decrease in resistance is below 10 % of their full capacity. Over this 10 % threshold, the components have heavy or extended damages and fall into class D. Their structural resistance should however remain at least 40 % of their full capacity. If not, the components belong to class E, indicating that the structural safety is inadequate and might not be covered by the partial safety factors [54].

When all components of a type are visible and accessible for visual inspection, each component is individually graded, and proportions for each damage class are obtained for each component type. The evaluation of the damage class is approximate, but the indication of size, incidence, consequence as well as the resistance reduction thresholds should give sufficient indication to carry out an informed classification. Nevertheless, the severity of damages is not always assessable by visual inspection. Thus, the damage class can be corrected after further investigations, such as those described in Table 2. For exemple, if the measured depth of carbonation is higher than the depth of cover concrete over the rebar, the damage class could be reduced by one class.

The degradation processes outlined in Table 1 are time dependant and at least partly caused by exposure to external factors such as chlorides, water or humidity, oxygen or high loads [66]. Their progression can be stopped or slowed down by eliminating the external factors and implementing appropriate damage treatment, as detailed in Table 1 and in Section 6.3. Therefore, in the specific context of evaluating the reuse potential of a component, the damage should be assessed at the time of deconstruction, without considering the time factor.



Damage class	Capacity reduction	Consequences
A good	-	-
B acceptable	-	Durability
C deviant	< 10%	Serviceability
D bad	>10 % < 40%	Serviceability and security
E failure	> 40%	Security

Fig. 5. Classification of damages by visual inspection. The grey rectangles symbolize the dimensions of the component.

5.4. Reporting

All the information collected through the previous steps must be reported synthetically and clearly for efficient use during the subsequent design phases. The following structure is proposed:

1. Introduction: basic information on the building, e.g., its location, construction year, use, and structural system;
2. Investigation methodology for the audit;
3. Investigation results;
4. Tables summarizing the inventory of components;
5. Factsheets for every component type, summarizing all collected information (a factsheet template is made available by the authors [64]).

6. Reusability grading

6.1. Purpose

The following sections describe a method to assess the reusability of RC structural components with regard to their long-term durability, which also impacts their structural safety. It aims to define the best solutions for reusing a disassembled RC component while reclaiming its structural potential as much as possible. Three factors are considered:

1. The preexisting damages, described by a *damage class* (Section 5.3)
2. The intended use in the receiving structure, described by a *use class* (Section 6.2)
3. The planned interventions on the component prior to reuse, described by an *intervention class* (Section 6.3).

As illustrated in Fig. 4, the damage class is the only factor established during the obsolete structure audit before the deconstruction of the donor building. The other two factors depend on the receiving project and serve as decision-support criteria for choosing a reasonable reuse strategy. It results in a *reusability grade* that expresses the proportionality of reusing an RC structural component and highlights the requirements in monitoring and control required for the receiving structure.

The reusability grade evaluates the long-term durability of reclaimed components but does not directly confirm their structural capacity for the new use. However, verifying structural capacity is another crucial aspect of the comprehensive reusability assessment, as outlined in Section 4.2, and should be concurrently addressed.

6.2. Use class

The structural and durability requirements for the reclaimed RC component relate to its function and exposition in the receiving structure, which is described by the *use class* listed in Table 5. The use class of a component depends first on the stability requirements in its new use, as listed in Table 3 and is adapted from the risk class proposed by Bertola and Brühwiler [54] for existing structures. In their work, the elements are classified on three levels based on the consequences of their failure when considering global structural safety. The same logic is adapted here to assess the stability requirements. To include concerns about the long-term durability of

Table 3
Stability definition, adapted from Bertola and Brühwiler [54].

Stability class	Failure consequence	Consequence for
No stability criteria	Limited	Serviceability only
Self-stable	Moderate	Structural safety or serviceability
Stable under external loads	Important	Structural safety and serviceability

Table 4
Water exposition levels.

Water exposition	Meaning	Exposition class [67, 68]	Exposition condition
Lightly exposed	Always dry	X0, XC1	Indoor component of a building with low humidity and not subject to frost, de-icing salts, sea salt, etc.
Moderately exposed	Moderately humid	XC3, XD1, XD3, XF1, XF2	Indoor component of a building with high humidity, outdoor surfaces protected from rain, surfaces exposed to frost, salt fog, etc.
Highly exposed	Alternately wet and dry	XC2, XC4, XD2, XF3, XF4	Surfaces exposed to rain, wet for long periods, surfaces exposed to de-icing salts and frost.

Table 5
Use class assignment based on the stability and water exposition.

Use class	Lightly exposed	Moderately exposed	Highly exposed
No stability criteria	I	II	III
Self-stable	II	III	IV
Stable under external loads	III	IV	V

reused components, the use class here also depends on the component's exposure to water in its new use, as defined in Table 4. Water exposition is expressed by the exposition class in the Swiss and European standards for concrete construction [67,68]. As a result, five use classes are possible, from I to V, from minimal to high structural and durability requirements.

The reclaimed component can belong to any use class if it can structurally assume the function while supporting the intended water exposition. During the components' inventory, described in Section 5.2, information is collected to determine the structural capacity of the components as well as their exposition class, which is linked to the concrete cover thickness and quality.

6.3. *Intervention class*

As stated earlier, the reuse potential of the components also depends on the level of interventions done on the component before the reassembly in the receiving structure. The need for intervention on the reclaimed component is defined during the design phase of the receiving project. The *intervention class*, listed in Table 6, describes the level of possible modifications, rehabilitation, or strengthening operations on the component. The intervention should remain proportionate from an economic and environmental point of view. Economic proportionality compares the cost and the benefit – i.e., risk reduction – that the intervention generates. This is a common principle when assessing existing structures [69], especially in the field of maintenance against seismic events [70]. Environmental proportionality compares the environmental impact – e.g., measured as $kgCO_2$ equivalent – between the intervention process and the production of a similar component with new RC. If the interventions are disproportionate from an economic or environmental point of view, then the reuse of the RC component should be reconsidered or questioned.

6.4. *Reusability grade*

The damage class, the use class, and the intervention class of a reclaimed RC component are combined according to the decision matrix in Fig. 6 to obtain the *reusability grade* described in Table 7. Based on the scoring developed to assess the condition of existing structures by Bertola and Brühwiler [54], reusability is graded on a 5-level scale. Components with a reusability grade of 1 or 2 are considered reusable. With a reusability grade of 3, reuse is questionable, while with a grade of 4 or 5, it is considered unsafe.

Table 6
Intervention class definition.

Intervention class	Maintenance measures	Geometry modifications
a	No action	No further cutting after extraction
b	Preventive maintenance, light strengthening	Simple cutting
c	Curative maintenance, rehabilitation, medium to important strengthening	Complex cutting or modification

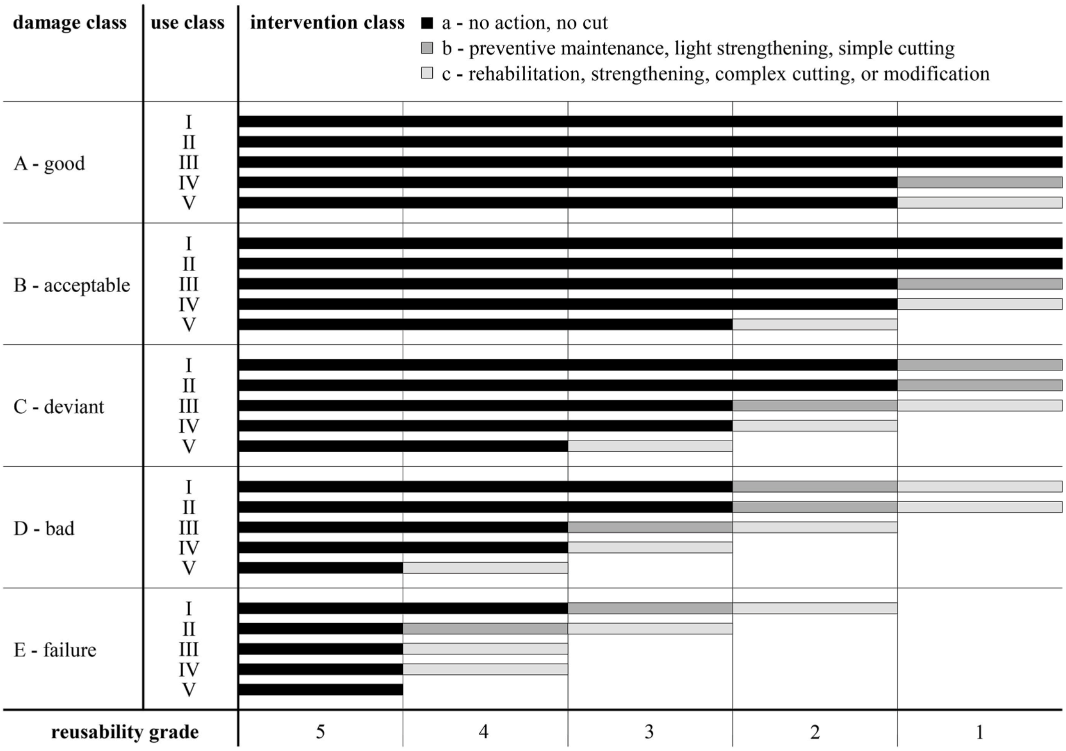


Fig. 6. Reusability grading decision matrix for durability assessment.

Table 7
Reusability grade definition.

Grade	Reusability	Description
1	Reusable	The component can be considered as good as new. Monitoring the component in the receiving structure should not differ from standard procedures existing for new structures.
2	Reusable with occasional controls	The component can be reused. Nevertheless, some minor damages or anomalies can affect the component's durability. It should be inspected occasionally with a particular emphasis on monitoring the evolution of these preexisting damages and anomalies. Interventions may be required earlier than for a new structure not to affect serviceability and security.
3	Questionable reuse	The reuse of the component is questionable as it cannot be guaranteed that the degradation process is under control. It is not excluded that the condition of the component degrades with resulting impacts on serviceability and structural safety. A reduction in the component's resistance must be considered, for instance, due to a loss of rebar section because of corrosion. Regular and careful inspections of the component must be carried out if reused. The cost and greenhouse gas emissions required to reuse such components may make the strategy questionable.
4	Not recommended reuse	The component presents damages that affect its structural safety. The damages are difficult to control, and the component resistance is significantly reduced. Even regular inspections are insufficient to guarantee the component's structural safety. Reuse of the component in not recommended.
5	Not reusable	The component presents damages that significantly affect its structural safety. It is not possible to reuse it under any circumstances.

The decision matrix allows a simplified risk assessment of the reuse of a component where the risk is expressed by the probability of a failure times the consequences [71]. The use class indicates a risk. It combines the probability of degradation with its consequence on stability loss and, thus, failure. The higher the damage class, the most probable the failure. On the contrary, the higher the intervention class, the lower the risk.

Bertola and Brühwiler [54] proposed a 5-level grading for the condition assessment of existing structures based on only two factors: the risk class and the degradation class. For the reusability grading, the risk class is translated into the use class, considering both stability and exposition, as described in Section 6.2. The degradation class is expressed here as the damage class. A third factor is introduced for the reusability grading: the intervention class. For use classes I to III and intervention class a, the decision matrix in Fig. 6 is therefore identical to the scoring proposed for existing structures. Using the same risk-based logic, the decision matrix is then extended for use classes IV and V, as well as intervention classes b and c.

The use and exposition of the component in the donor building are considered in the decision matrix through the damage class. It considers the component's degradation over time during its initial use. Components exposed to water (moderately or highly in Table 4) have a higher probability of being damaged and are consequently graded in a higher damage class and hence a lower reusability grade. A component with a damage class A is considered as good as a newly produced one and can be reused for any use class defined in Table 5, provided that its design is sufficient to resist the loading and exposition demands. However, for the more demanding use classes IV and V, when the component might be exposed to water while resisting external loads, preventive maintenance, transformation, or even strengthening (transformation class b or c) can be required to obtain a reusability grade 1. Indeed, most components available for reuse will have been designed under former standards, and the transformation will ensure that the component meets current standards for concrete structures. For example, increasing the concrete cover thickness over the reinforcement bars or providing flexural strengthening might be required. As the damage class increases (class B and C), transformation of the components becomes necessary to reach a reusability grade of 1, particularly for use classes implying external loads or water exposition (class III or higher). In the case of damage classes D or E, it is nearly impossible to reach a reusability grade of 1, and the reuse of such components without major transformation is questionable or not recommended. Therefore, components falling in those damage classes are generally discarded.

The matrix allows designers to choose the most objective, proportionate, and adapted reuse strategy for a given project while insuring long-term durability and avoiding the premature downcycling of the reclaimed RC component. Because of its design nature, the decision matrix will lead to different outcomes depending on the designers' intents, objectives set by the clients, or technical, economic, and environmental constraints.

7. Case studies

7.1. Description of the buildings

This section describes the three building case studies (BCS) for which the authors were mandated to evaluate the reuse potential of the RC structural components (BCS1 [72], BCS2 [73], and BCS3 [74]). These BCS were used to develop and test the obsolete structure audit presented in Section 5 and the reusability grading presented in Section 6. The facades of the three buildings are pictured in Fig. 2. Basic information on the five building case studies is provided in Table 8.

The inventory was completed for all buildings using original construction drawings and limited on-site investigation. For all five building case studies, the volumetric ratios of the different structural material types and component categories are illustrated in Fig. 7 (a) and (b), respectively. The buildings are mainly made of cast-in-place RC. As shown by other authors [75,76] for various building types, slabs, in grey in Fig. 7(b), represent the largest volume of structural components.

Table 8
Basic information of the five building case studies.

Information	BCS 1	BCS 2	BCS 3
Construction year	1964–1969	1975	1960–1965
Number of floors (incl. underground floors)	16	3	6
Building floor area	1500 m^2	2875 m^2	660 m^2
Volume of structural construction materials	7000 m^3	4845 m^3	876 m^3
Construction drawings available?	Yes	Yes	Yes
Formwork and reinforcement drawings available?	Yes	No	No

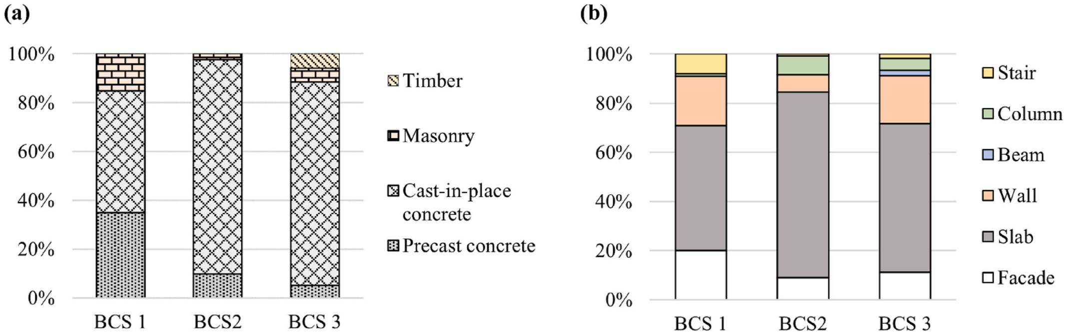


Fig. 7. Volumetric ratios of (a) structural material types and (b) component categories in the building case studies.

7.2. Damage assessment results

As part of the procedure described in Section 4.2, a visual inspection was done on the structural components of BCS1 to 3 to evaluate their condition and classify the damage according to Section 5.3 and Fig. 5. The results are shown in Fig. 8, distinctively for indoor and outdoor components.

More than 80 % of the RC components belong to damage class A – i.e., good condition – and therefore have a durability that allows easy reuse. Furthermore, according to these three building case studies, 100 % of indoor RC components are in damage class A, which corresponds to the largest volumetric part of building components. This highlights that, in indoor conditions, when not exposed to water and at normal humidity levels, concrete remains in good condition. On the other hand, the damage classification of outdoor components is more variable. BCS 1 and BCS 3 have around 80 % of their facade component with a damage class of A or B – i.e., good or acceptable conditions. In contrast, BCS 2 has more than 80 % of its components in damage classes C, D, or E – i.e., deviant, bad, or failure conditions. In addition, in two case studies, investigations showed that the depth of carbonation and the extent of rebar corrosion in the facade components had a non-negligible influence on their condition, which was not detected during visual inspection. This led to a reduction of their damage class.

7.3. Reusability grading

As introduced in Section 6, reusability is graded using a decision matrix, allowing to evaluate various reuse strategy when designing the receiving structure. For BCS 1 to 3, different scenarios are considered to analyze the reusability potential of their component:

- Identical reuse: No change of use class for all RC components – i.e., same stability and exposition condition according to Tables 3 and 4 – and no transformation between the donor and receiving buildings – i.e., intervention class a according to Table 6. For

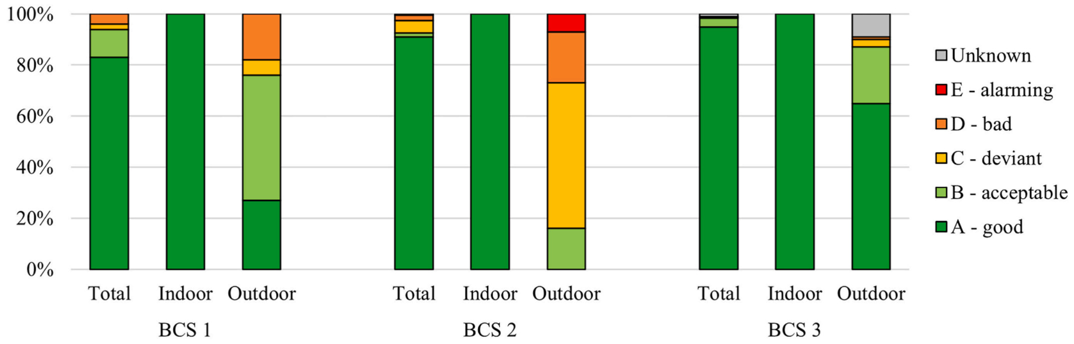


Fig. 8. Damage assessment of RC components highlighting differences between indoor and outdoor components.

instance, an indoor slab is reused as an indoor slab, or an outdoor self-supporting facade panel is reused as an outdoor self-supporting one.

- Rehabilitation and reuse: No change of use class for all RC components but possibility of intervention class c, according to Table 6. For example, a damaged façade panel (damage class C) is transformed by repairing the zones of spalled concrete with mortar and eventually cutting out the parts with corroded rebars. It is then reused again as a façade panel in the receiving building.
- Downcycling reuse: Reduction of use class by one degree, according to Table 5–i.e., reduction of stability or exposition criterion – and no transformation – i.e., intervention class a according to Table 6. For exemple, an indoor slab is reused as an indoor self-supporting wall, or an exterior self-supporting facade panel is reused as an indoor self-supporting wall.

For each of these scenarios, the resulting reusability ratios of the RC components for the three BCS are presented in Fig. 9. It shows that almost 90 % of the elements are considered reusable in the case of identical reuse. By modifying the use class (downcycling reuse scenario), the reusability ratio approaches 95 %. With targeted interventions (rehabilitation and reuse scenario), it approaches 100 %. However, the proportionality of these interventions, regarding both costs and detrimental environmental impacts, should also be verified. The components whose reuse is questionable or impossible are the damaged facade elements, representing a minimal part of the total volume of the construction elements, as expressed in Fig. 7. Their reuse potential for more demanding use classes could be increased with interventions, but these are more susceptible to being disproportionate. For BCS2 and a downcycling reuse scenario, reducing the use class with no intervention for the damaged (mainly damage class C to E) self-stable highly exposed facade panels does not change the reusability grading, according to Fig. 6. In contrast, for BCS1 and BCS3, which also concerns highly exposed façade components stable under external load, the reusability grading changes with a downcycling scenario.

Table 9 details, for each BCS, the volume of reuseable RC components and the equivalent factors used to calculate the environmental savings for the identical reuse scenario. For BCS1, BCS2, and BCS3, this scenario would save about 1505 tCO_2-eq, 1085 tCO_2-eq, and 200 tCO_2-eq, respectively, if compared to a scenario in which the old RC components are demolished, and similar ones are newly produced with recycled concrete. Transportation from factory to site is however not considered in those estimations.

These case studies show that the potential for reuse of facade elements is limited. On the other hand, the indoor structural elements, which represent the largest proportion of a building's load-bearing structure, are likely to have a high reuse potential, independent of the reuse scenario opted for in the design of the new construction.

8. Discussion

8.1. Contribution

This paper presents a procedure to audit an obsolete structure and assess the reusability of its structural RC components at the early stage of deconstruction and new construction projects. It is thought to be realized on any soon-to-be-demolished buildings. It allows an informed decision between various reuse design alternatives, facilitating the design process when integrating reclaimed structural RC components in new projects. The work filled the four research gaps highlighted in Section 2.5.

In response to the first and second research gaps on the lack of procedure to collect information on structural RC and evaluate their reuse potential, this paper proposes a straightforward method in Section 5. The aim is to inventory, classify and characterize a stock of structural components by identifying the relevant information required for later reuse. For each component type, the information is then summarized in factsheets to be used by designers. It is then completed by the reusability grading proposed in Section 6, which allows for exploring different reuse strategy for components with regard to their durability.

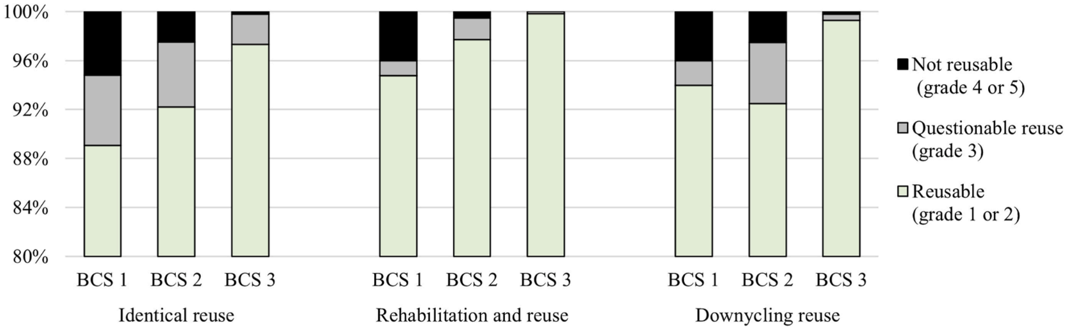


Fig. 9. Reuse potential ratios of the components based on different scenarios: identical reuse, rehabilitation and reuse, and downcycling reuse.

Table 9
Environmental savings for the identical reuse scenario.

	BCS 1	BCS 2	BCS 3
Reusable volume of RC components (m^3)	5900	4250	786
Equivalent factor for production and elimination of RC components [65] ($kgCO_{2\text{-eq}}/kg$)	0.102	0.102	0.102
Environmental savings ($tCO_{2\text{-eq}}$)	**1505**	**1085**	**200**

In response to the third research gap on the lack of condition assessments for RC structures specific to reuse goals, the reusability grading presented in Section 6 helps assessing how damages impact the reuse potential of a component with regard to durability, serviceability, and structural safety. For each grade, described in Section 6.4, recommendations are given on the levels of monitoring and control required for a reused component in the receiving project.

Finally, in response to the fourth research gap on the lack of routine damage treatments for RC components that consider changes in function, exposition, or component geometry, the reusability grading presented in Section 6 introduces a use class (Section 6.2) to qualify change in structural role and exposition, as well as an intervention class (Section 6.3) to qualify various levels of geometric modification or material reparation.

8.2. *Experience feedback*

As exposed in Section 2.1, the lack of systematic procedure to assess the reusability of RC components was identified as a barrier by experts and previous studies [11]. Continuous feedback from the different stakeholders (owner, planner, designer, construction company) of the three building case studies allowed adapting to their needs the procedures, the reports, and the data provided in the factsheet of the audit. Nevertheless, the outcome presented in this paper raised additional questions, particularly on constructive detailing – e.g., regarding fire resistance or the evolution of the damages in time.

The factsheets – following the structure of the proposed template [64] – have proven to be a valuable tool to summarize all the collected data later required to design with the reclaimed components. They have been used as input data for three design competitions and have allowed the design of new structures with reclaimed RC components. As it turned out, they do not limit the designers' creativity. Indeed, the audit focuses on evaluating the obsolete structure and does not propose any solution for integrating the components into a new receiving project.

On the other hand, some owners and planners involved in the building case studies demanded the integration of potential structural typologies for the future reassembly of the components, in concordance with their structural capacity and durability. The reusability grading decision matrix introduced in Section 6 allowed the authors to evaluate whether the reuse of the components is reasonable regarding preexisting damages and for different new use cases. Although it appeared to be a necessary check, one must keep in mind that the other factors mentioned in Fig. 4 – i.e., *structural capacity*, *constructive detailing*, *logistics*, and *quantity* – also significantly impact the reuse potential of RC components.

8.3. *Future work*

In future steps of this work, the reusability assessment should be completed with methods to further evaluate the structural capacity of components, as shortly introduced in Section 5.2 for the case when no construction drawing is available. In general, more indications on the structural capacity of the components could be given, expressed with possible future structural typologies and related maximum live loads for different spans or configurations. This would give a better insight into the structural reusability of the reclaimed RC components. Moreover, the procedure should also encompass the next steps of the project and include inspection and validation protocols. The goal of these subsequent protocols would be to ensure that the reclaimed components maintain the value they were given during the obsolete structure audit and still fit the requirements of their new use once they arrive on the new construction site. Other research is also required to understand how the reclaimed components can be adapted to current standards requirements, such as minimal concrete cover for durability or fire resistance, and component thickness for phonic resistance.

In the longer term, it would be ideal to extend the assessment of existing building structures presented in this paper to rehabilitation and adaptive reuse. A standardized procedure would help make objective decisions about the best circular strategies to adopt – i.e., rehabilitation, adaptive reuse, component reuse, or recycling – for each existing structure, aiming to reduce demolition as much as possible.

9. Conclusions

Reusing RC components is a little-explored strategy to reduce the detrimental environmental impact of the concrete industry. It consists in carefully extracting RC components of a donor structure that will soon be demolished to reuse them in a new receiving structure. Compared to a standard project sequence, reuse implies changes in the project phases, synthesized by the ideal design sequence proposed in this paper and summarized in the following sentences. At the early stage of both deconstruction and construction projects, it first integrates an audit of the obsolete structure to characterize the RC components and provide all valuable information for designing with them. The reusability of the components is then assessed for a defined new use in the receiving structure. It must consider four factors: durability, structural capacity, constructive detailing, and logistics. As the more complex and subjective factor, this paper delved into the assessment of the component's durability and suggested a reusability grading based on it. It is a design tool, in the form of a decision matrix, to help designers evaluate the reuse potential of RC components. It involves three factors: the damage class, the use class, and the intervention class. The first describes the existing donor structure state, and the last two the new receiving structural concept. It allows adapting the design at the early stage of the project, which is less costly and leads to more successful integration of reused RC components.

The procedure was presented to practitioners, reuse or structural maintenance experts, and used in workshops and design competitions. Feedback highlighted the applicability of the procedure and the value of having a systematic reusability assessment of obsolete soon-to-be-demolished structures. In addition, the procedure was applied to three building case studies, showing encouraging results regarding the reuse potential of the buildings. More than 80 % of building components were assessed in good condition. The other components only concern facade components. The reuse potential of the components was then assessed with the proposed decision matrix. The results show that more than 90 % of the components are reusable under an identical use scenario, 95 % if a downcycling scenario is considered (e.g. through a reduction of the use demand), and almost 100 % if applying rehabilitation measures.

The challenge remains to integrate such a procedure systematically at the beginning of obsolete structure demolition projects, either through regulation – e.g., as a mandatory condition for receiving a building demolition permit – or incentivization – e.g., by advertising the environmental and economic benefits of the approach, especially for managers of large real estate. New reuse projects would ultimately ensue, with significant savings of demolition waste, raw material extraction, and greenhouse gas emissions.

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CRediT authorship contribution statement

Julie Devènes: Conceptualization, Data curation, Formal analysis, Methodology, Visualization, Writing – original draft. **Maléna Bastien-Masse:** Conceptualization, Funding acquisition, Methodology, Project administration, Supervision, Writing – review & editing. **Corentin Fivet:** Conceptualization, Funding acquisition, Supervision, Writing – review & editing.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Malena Bastien-Masse reports financial support was provided by Immobilien Basel-Stadt, CH.

Data availability

No data was used for the research described in the article.

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References

[1] P.J.M. Monteiro, S.A. Miller, A. Horvath, Towards sustainable concrete, Nat. Mater. 16 (2017) 698–699, https://doi.org/10.1038/nmat4930.

[2] G. Habert, Y. Bouzidi, C. Chen, A. Jullien, Development of a depletion indicator for natural resources used in concrete, Resour. Conserv. Recycl. 54 (2010) 364–376, https://doi.org/10.1016/j.resconrec.2009.09.002.

[3] S.A. Miller, A. Horvath, P.J.M. Monteiro, Impacts of booming concrete production on water resources worldwide, Nat. Sustain. 1 (2018) 69–76, https://doi.org/10.1038/s41893-017-0009-5.

[4] A. Thomsen, K. Van Der Flier, Replacement or renovation of dwellings: the relevance of a more sustainable approach, Build. Res. Inf. 37 (2009) 649–659, https://doi.org/10.1080/09613210903189335.

[5] D.M. Abramson, Obsolescence: an Architectural History, The University of Chicago Press, Chicago; London, 2016.

[6] S. Giorgi, M. Lavagna, A. Campioli, Guidelines for effective and sustainable recycling of construction and demolition waste, in: E. Benetto, K. Gericke, M. Guiton (Eds.), Des. Sustain. Technol. Prod. Policies, Springer International Publishing, Cham, 2018, pp. 211–221, https://doi.org/10.1007/978-3-319-66981-6_24.

[7] A. Favier, C. De Wolf, K. Scrivener, G. Habert, A Sustainable Future for the European Cement and Concrete Industry: Technology Assessment for Full Decarbonisation of the Industry by 2050, ETH Zurich, 2018, https://doi.org/10.3929/ethz-b-000301843.

[8] G. Habert, S.A. Miller, V.M. John, J.L. Provis, A. Favier, A. Horvath, et al., Environmental impacts and decarbonization strategies in the cement and concrete industries, Nat. Rev. Earth Environ. 1 (2020) 559–573, https://doi.org/10.1038/s43017-020-0093-3.

[9] A.T.M. Marsh, A.P.M. Velenturf, S.A. Bernal, Circular economy strategies for concrete: implementation and integration, J. Clean. Prod. (2022) 132486, https://doi.org/10.1016/j.jclepro.2022.132486.

[10] C. Knoeri, E. Sanyé-Mengual, H.-J. Althaus, Comparative LCA of recycled and conventional concrete for structural applications, Int. J. Life Cycle Assess. 18 (2013) 909–918, https://doi.org/10.1007/s11367-012-0544-2.

[11] C. Küpfer, M. Bastien-Masse, C. Fivet, Reuse of concrete components in new construction projects: critical review of 77 circular precedents, J. Clean. Prod. 383 (2023) 135235, https://doi.org/10.1016/j.jclepro.2022.135235.

[12] S. Heyn, A. Mettke, C. Thomas, Rückbau industrieller Bausubstanz - Großformatige Betonelemente im ökologischen Kreislauf : Schlussbericht zum Forschungsvorhaben. Teil 2: Wieder- und Weiterverwendung großformatiger Betonbauteile [Deconstruction of industrial buildings - Large-format concrete elements in the environmental cycle : Final report on the research project. Part 2: Reuse and further use of large-format concrete elements]. Cottbus: Brandenburg University of Technology (BTU), Fakultät für Umweltwissenschaften und Verfahrenstechnik, Lehrstuhl Altlasten, Fachgruppe Bauliches Recycling, 2008.

[13] U. Dechantsreiter, P. Horst, A. Mettke, S. Asmus, S. Schnmidt, F. Knappe, et al., Instrumente zur Wiederverwendung von Bauteilen und hochwertigen Verwertung von Baustoffen. [Instruments for the reuse of structural components and high-quality utilization of building materials]. Bremen, Cottbus & Heidelberg, Umweltbundesamt, 2015.

[14] S. Huuhka, N. Naber, C. Asam, C. Caldenby, Architectural potential of deconstruction and reuse in declining mass housing estates, Nord J. Archit. Res. 31 (2019).

[15] Superlocal, Expogebouw [Exhibition building], SUPERLOCAL, 2018. https://www.superlocal.eu/superlocal/expogebouw/. (Accessed 25 November 2022).

[16] Superlocal, Update bouw drie circulaire proefwoningen [Update of the construction of three circular pilot homes], SUPERLOCAL, 2020. https://www.superlocal.eu/update-bouw-drie-circulaire-proefwoningen/. (Accessed 21 July 2022).

[17] J. Devènes, J. Brütting, C. Küpfer, M. Bastien-Masse, C. Fivet, Re:Crete – reuse of concrete blocks from cast-in-place building to arch footbridge, Structures 43 (2022) 1854–1867, https://doi.org/10.1016/j.istruc.2022.07.012.

[18] M. Gorgolewski, Designing with reused building components: some challenges, Build. Res. Inf. 36 (2008) 175–188, https://doi.org/10.1080/09613210701559499.

[19] C.M. Rose, J.A. Stegemann, From waste management to component management in the construction industry, Sustainability 10 (2018) 229, https://doi.org/10.3390/su10010229.

[20] B. Addis, Building with Reclaimed Components and Materials: A Design Handbook for Reuse and Recycling, Routledge, London, 2006, https://doi.org/10.4324/

9781849770637.

[21] M. Ghyoot, L. Devlieger, L. Billiet, Déconstruction et réemploi: Comment faire circuler les éléments de construction [Deconstruction and reuse: How to circulate building components], Presses Polytechniques et Universitaires Romandes, Lausanne, 2018.

[22] Opalis. materials n.d. https://opalis.eu/en/materials (accessed June 8, 2023).

[23] M. Gorgolewski, Resource Salvation: the Architecture of Reuse, Wiley, Hoboken, NJ, 2017.

[24] E. Stricker, G. Brandi, A. Sonderegger, M. Angst, B. Buser, M. Massmünster, et al. (Eds.), Bauteile wiederverwenden: ein Kompendium zum zirkulären Bauen, Park Books, Zürich, 2021.

[25] M. Eklund, S. Dahlgren, A. Dagersten, G. Sundbaum, The Conditions and Constraints for Using Reused Materials in Building Projects, Proc. 11th Rinker Int. Conf., Rotterdam, The Netherlands, 2003.

[26] C.F. Dunant, M.P. Drewniok, M. Sansom, S. Corbey, J.M. Allwood, J.M. Cullen, Real and perceived barriers to steel reuse across the UK construction value chain, Resour. Conserv. Recycl. 126 (2017) 118–131, https://doi.org/10.1016/j.resconrec.2017.07.036.

[27] D. Densley Tingley, S. Cooper, J. Cullen, Understanding and overcoming the barriers to structural steel reuse, a UK perspective, J. Clean. Prod. 148 (2017) 642–652, https://doi.org/10.1016/j.jclepro.2017.02.006.

[28] C.F. Dunant, M.P. Drewniok, M. Sansom, S. Corbey, J.M. Cullen, J.M. Allwood, Options to make steel reuse profitable: an analysis of cost and risk distribution across the UK construction value chain, J. Clean. Prod. 183 (2018) 102–111, https://doi.org/10.1016/j.jclepro.2018.02.141.

[29] S. Brand, How Buildings Learn: what Happens after They're Built, Penguin Books, New York, NY Toronto London, 1995.

[30] M.R. Hosseini, R. Rameezdeen, N. Chileshe, S. Lehmann, Reverse logistics in the construction industry, Waste Manag. Res. 33 (2015) 499–514, https://doi.org/10.1177/0734242X15584842.

[31] C. Küpfer, C. Fivet, Déconstruction Sélective - Construction Réversible: recueil pour diminuer les déchets et favoriser le réemploi dans la construction [Selective Deconstruction - Reversible Construction: Compendium to decrease waste and encourage component reuse in the construction industry], Ecole Polytech Fédérale Lausanne EPFL, 2021, https://doi.org/10.5281/zenodo.4314325.

[32] J. Brütting, G. Senatore, M. Schevenels, C. Fivet, Optimum design of frame structures from a stock of reclaimed elements, Front Built. Environ. 6 (2020), https://doi.org/10.3389/fbuil.2020.00057.

[33] M. Fujita, T. Masuda, Application of various NDT methods for the evaluation of building steel structures for reuse, Materials 7 (2014) 7130–7144, https://doi.org/10.3390/ma7107130.

[34] J. Yeung, S. Walbridge, C. Haas, The role of geometric characterization in supporting structural steel reuse decisions, Resour. Conserv. Recycl. 104 (2015) 120–130, https://doi.org/10.1016/j.resconrec.2015.08.017.

[35] P. Keller, J. McConnell, T. Schumacher, E.T. Thostenson, Construction stress monitoring using a wireless sensor network to evaluate reuse potential of structural steel, J. Struct. Eng. 145 (2019) 04019143, https://doi.org/10.1061/(ASCE)ST.1943-541X.0002384.

[36] A. Cavalli, L. Bevilacqua, G. Capecchi, D. Cibecchini, M. Fioravanti, G. Goli, et al., MOE and MOR assessment of in service and dismantled old structural timber, Eng. Struct. 125 (2016) 294–299, https://doi.org/10.1016/j.engstruct.2016.06.054.

[37] S. Seys, L. Billiet, M. Gielen, M. Ghyoot, Vade-mecum pour le réemploi hors-site - Comment extraire les matériaux réutilisables de bâtiments publics ?[Vade-mecum for Off-Site Reuse], Rotor asbl, Anderlecht, 2015.

[38] T. Smeyers, M. Deweerdt, M. Mertens, Reuse Toolkit - the Reclamation Audit. Interreg NWE 739 -FCRBE, 2022.

[39] FCRBE, Review of Existing Pre-demolition Tools, Policies, Resources for Identifying, Quantifying and Organizing the Reclamation of Reusable Elements, Interreg NWE 739 - FCRBE, 2019.

[40] B. Guy, E.M. Gibeau, A Guide to Deconstruction, Deconstruction Institute, Florida, USA, 2003.

[41] J. Benoit, G. Saurel, M. Billet, F. Bougrain, S. Laurenceau, Le réemploi passerelle entre architecture et industrie [REPAR 2 : Reuse to bridge architecture and insdustry]. ADME, CSTB, Bellastock, 2018.

[42] L.B.V. Merkblatt, FertigteileWiederverwendung von Fertigteilen aus Beton-, Stahl- und Spannbeton [Code of practice for reuse of precast elements made of concrete, reinforced and prestressed concrete], Landesmt für Bauen und Verkehr des Landes Brandenburg, 2012.

[43] Standards Norway. NS 3682:2022 - Hollow Core Slabs for Reuse, Standards Norway, 2022.

[44] K.F. Gustafsson, V. Cutler, F. Høgdal, D.L. Vind, Concrete Reuse Classification, Lendager & DTU (Technical University of Denmark), Denmark, 2022.

[45] M.W.F. Vullings, S.N.M. Wijte, S. Huuhka, Guidelines for a BIM-Aided Pre-deconstruction Audit, The ReCreate project, 2022.

[46] B.R. Ellingwood, Risk-informed condition assessment of civil infrastructure: state of practice and research issues, Struct. Infrastruct. Eng. 1 (2005) 7–18, https://doi.org/10.1080/15732470412331289341.

[47] J.F. Falorca, J.P.N.D. Miraldes, J.C.G. Lanzinha, New trends in visual inspection of buildings and structures: study for the use of drones, Open Eng. 11 (2021) 734–743, https://doi.org/10.1515/eng-2021-0071.

[48] M. Omer, L. Margetts, M.H. Mosleh, L.S. Cunningham, Inspection of concrete bridge structures: case study comparing conventional techniques with a virtual reality approach, J. Bridge Eng. 26 (2021) 05021010, https://doi.org/10.1061/(ASCE)BE.1943-5592.0001759.

[49] M.V. Piras, F. Mistretta, M.L. Fadda, L. Deias, A reliable visual inspection method for vulnerability assessment of hyperstatic structures using fuzzy logic analysis, J. Constr. Eng. 2015 (2015) e171989, https://doi.org/10.1155/2015/171989.

[50] J. Bennetts, G. Webb, S. Denton, P.J. Vardanega, N. Loudon, Quantifying Uncertainty in Visual Inspection Data, Maint Saf Risk Manag Life-Cycle Perform Bridg, 2018, p. 2252.

[51] M.I. Serralheiro, J. de Brito, A. Silva, Methodology for service life prediction of architectural concrete facades, Construct. Build. Mater. 133 (2017) 261–274, https://doi.org/10.1016/j.conbuildmat.2016.12.079.

[52] C. Pellegrino, A. Pipinato, C. Modena, A simplified management procedure for bridge network maintenance, Struct. Infrastruct. Eng. 7 (2011) 341–351, https://doi.org/10.1080/15732470802659084.

[53] K. Schellenberg, T. Vogel, M. Chèvre, M. Alvarez, Assessment of bridges on the Swiss national roads, Struct. Eng. Int. 23 (2013) 402–410, https://doi.org/10.2749/101686613X13627351081759.

[54] N.J. Bertola, E. Brühwiler, Risk-based methodology to assess bridge condition based on visual inspection, Struct. Infrastruct. Eng. 0 (2021) 1–14, https://doi.org/10.1080/15732479.2021.1959621.

[55] V. Gattulli, L. Chiaramonte, Condition assessment by visual inspection for a bridge management system, Comput. Aided Civ. Infrastruct. Eng. 20 (2005) 95–107, https://doi.org/10.1111/j.1467-8667.2005.00379.x.

[56] A.M. Neville, Properties of Concrete: Standards Updated to 2002, 4th and final ed., repr ed., Pearson Education, Harlow, 2006.

[57] D. Breysse, 3 - deterioration processes in reinforced concrete: an overview, in: C. Maierhofer, H.-W. Reinhardt, G. Dobmann (Eds.), Non-Destr. Eval. Reinf. Concr. Struct., vol. 1, Woodhead Publishing, 2010, pp. 28–56, https://doi.org/10.1533/9781845699536.1.28.

[58] J.B. Newman, B.S. Choo, Advanced Concrete Technology, Butterworth-Heinemann, Oxford, England Burlington, MA, 2003.

[59] E. Cavaco, C. Andrade, J. Appleton, V. Bouteiller, S. Cabral Fonseca, M. Carballo, et al., Fib Bulletins 102. Guide for Protection and Repair of Concrete Structures. Fib, The International Federation for Structural Concrete, 2022, https://doi.org/10.35789/fib.BULL.0102.

[60] W. Wai-Lok Lai, X. Dérobert, P. Annan, A review of ground penetrating radar application in civil engineering: a 30-year journey from locating and testing to imaging and diagnosis, NDT E. Int. 96 (2018) 58–78, https://doi.org/10.1016/j.ndteint.2017.04.002.

[61] C. Bofinger, K. Müller, B. Vallance, Triemli Personalhäuser Wiederverwenden - Ideenworkshop und Wissensaustausch zur Wiederverwendung von Stahlbeton [Reusing Triemli buildings - ideas workshop and knowledge exchange on the reuse of reinforced concrete], Zürich: Zirkular, 2022.

[62] C. Küpfer, M. Bastien-Masse, J. Devènes, C. Fivet, Environmental and economic analysis of new construction techniques reusing existing concrete elements: two case studies, IOP Conf. Ser. Earth Environ. Sci. 1078 (2022) 012013, https://doi.org/10.1088/1755-1315/1078/1/012013.

[63] Baubüro in situ, Zirkular, Ortbeton Wiederverwenden [Reusing in-situ concrete], Espazium, 2023. https://www.espazium.ch/de/aktuelles/kreislaufwirtschaft-beton-werkstadt-sbb. (Accessed 28 February 2023).

[64] J. Devènes, M. Bastien-Masse, C. Fivet, Factsheet Template for Reinforced Concrete Components - Obsolete Structure Audit, Fribourg: Ecole Polytechnique Fédérale de Lausanne (EPFL), 2023, https://doi.org/10.5281/zenodo.8043091.

[65] Koordinationskonferenz der Bau- und Liegenschaftsorgane der öffentlichen Bauherren KBOB. Ökobilanzdaten im Baubereich 2009/1:2016, https://www.kbob.admin.ch/kbob/de/home/themen-leistungen/nachhaltiges-bauen/oekobilanzdaten_baubereich.html, 2016. (Accessed 3 November 2021).

[66] C. Wang, Q. Li, B.R. Ellingwood, Time-dependent reliability of ageing structures: an approximate approach, Struct. Infrastruct. Eng. 12 (2016) 1566–1572, https://doi.org/10.1080/15732479.2016.1151447.

[67] S.I.A. Swiss, Standard SIA 262:2013 - Concrete Structures, 2013.

[68] Eurocode 2: Design of Concrete Structures - Part 1-1 :general Rules and Rules for Buildings, British Standards Institution, London, 2015.

[69] S.I.A. Swiss, Standard SIA 269:2011 - Existing Structures - Basis, 2011.

[70] S.I.A. Swiss, Standard SIA 269/8:2017 - Existing Structures - Earthquakes, 2017.

[71] M. Rausand, S. Haugen, Risk Assessment: Theory, Methods, and Applications, second ed., John Wiley & Sons, Hoboken, NJ, 2020.

[72] J. Devènes, M. Bastien-Masse, C. Küpfer, C. Fivet, Zürich Stadtspital Triemli Personalhäuser – Resource assessment of structural elements. Fribourg and Zürich: Ecole Polytechnique Fédérale de Lausanne (EPFL) and Stadt Zürich, 2022, https://doi.org/10.5281/zenodo.6020923.

[73] J. Devènes, M. Bastien-Masse, C. Fivet, Basel – lagerhalle erlenmatt ost – resource assessment of structural components, in: Fribourg and Basel: Ecole Polytechnique Fédérale de Lausanne (EPFL) and Immobilien Basel-Stadt (IBS), 2022, https://doi.org/10.5281/zenodo.7894589.

[74] J. Devènes, N. Widmer, M. Bastien-Masse, Basel – Socinstrasse 55a, 57 and 59 – Resource Assessment of Structural Components, Fribourg and Basel: Ecole Polytechnique Fédérale de Lausanne (EPFL) and Immobilien Basel-Stadt (IBS), 2023, https://doi.org/10.5281/zenodo.7732838.

[75] P. Foraboschi, M. Mercanzin, D. Trabucco, Sustainable structural design of tall buildings based on embodied energy, Energy Build. 68 (2014) 254–269, https://doi.org/10.1016/j.enbuild.2013.09.003.

[76] M. Sansom, R.J. Pope, A comparative embodied carbon assessment of commercial buildings, Struct. Eng. 90 (2012) 38–49.