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Review

Reuse of concrete components in new construction projects: Critical review of 77 circular precedents

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A R T I C L E I N F O

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A B S T R A C T

Extracting pieces of concrete from obsolete buildings and reusing them, as is, in new assemblies is today rarely considered a strategy for improving the sustainability of the construction sector. By delaying the crushing of concrete into aggregates and avoiding the need for fresh cement in new buildings, the circular strategy is however expected to reduce greenhouse gas emissions and threats to natural ecosystems. In reaction, the authors postulate that (1) built precedents of Piecewise Reuse of Extracted Concrete in new Structures (PRECS) have existed for several decades, (2) a large diversity of proven implementation techniques is readily available but knowledge is fragmented, (3) barriers to a broader adoption can be inferred from the existing documentation and are largely transitional. To support these postulates, this study first builds an original collection of 77 PRECS projects designed between 1967 and 2022 in Europe and the U.S.A. Next, a diachronic analysis determines seven historical trends and three periods since 1967, shedding new light on the development of PRECS and its design possibilities. Supporting and limiting forces for a broader adoption of PRECS are then identified through a synchronic analysis. Recommendations for future research directions are also given. In conclusion, this paper demonstrates that the reuse of concrete components is a practice with already a long history and several successful operations in terms of environmental impact and cost, which hence supports the potential of PRECS to become a more widespread strategy of cleaner construction.

1. Introduction

1.1. Strategies to reduce the environmental impact of the concrete industry

Concrete is the most consumed material in the world, with 30 gigatons of annual demand (Monteiro et al., 2017). In Europe, concrete waste alone contributes about 30% of the total mass of solid waste (Böhmer et al., 2008). Made of sand and gravel bonded together by cement reacted to water, concrete is a major cause of environmental and, to a certain degree, health degradation. Due primarily to energy-intensive clinker production, the yearly 4-gigaton cement production worldwide (IEA, 2021) is responsible for 9% of anthropogenic greenhouse gas emissions (Monteiro et al., 2017). With an ever-growing demand, concrete production today accounts for a high share of air pollutants (Miller and Moore, 2020), and both the extraction of its raw materials and the landfilling of its waste threaten landscapes, biodiversity and ecosystems (Ioannidou et al., 2017; Peduzzi, 2014).

Strategies to reduce the Detrimental Environmental Impact (DEI) of the concrete industry are well known (Habert et al., 2020; Marsh et al., 2022). Yet, more stringent application of these strategies and development of new ones are needed, as the direct CO_2 intensity of cement production globally increased by 1.8% per year between 2015 and 2020 (IEA, 2021). Fig. 1 presents the concrete value chain, from manufacturing to end-of-life. Shown in blue are direct strategies to lower concrete-related greenhouse gas emissions. They include using alternative fuels for clinker production, implementing carbon capture and storage strategies, substituting a share of the clinker with other products in cement production, reducing the amount of cement in concrete mixes or minimizing the needed volume of concrete through design efficiency (Habert et al., 2020). Although allowing reductions of CO_2 emissions per produced concrete mass, those strategies are not sufficient to fully eliminate the DEI of the concrete industry.

In addition to the aforementioned direct strategies, Circular Economy strategies, shown in green and red on Fig. 1, further aim to limit waste accumulation, prolong the use of concrete and introduce material

Abbreviations: PRECS, Piecewise Reuse of Extracted Concrete in new Structures; DEI, Detrimental Environmental Impact.

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recovery loops. As presented in the Delft Ladder, which prioritizes waste-management strategies according to their expected ecological footprint (Hendriks and Janssen, 2003), circular strategies should be implemented as follows: (1) extend the use of structures as long as possible without modification, (2) repair or rehabilitate them if needed, (3) if building removal is unavoidable, deconstruct it and reuse its pieces in another project with minimal reprocessing, (4) if components are not reusable, recycle them into the manufacture of a similar or different product.

When it comes to concrete structures, the 4th circular strategy consists in crushing and downcycling it as backfilling material in excavated areas and engineering works (Zhang et al., 2022) or as replacement of natural aggregates in what is commonly called "*recycled* concrete". Compared to conventional concrete, recycled concrete limits waste generation and resource depletion but does not emit fewer greenhouse gases per cubic meter than conventional concrete (Marinković et al., 2010), since a similar or higher quantity of cement is required to achieve the same strength.

This research focuses on the 3rd circular strategy, red in Fig. 1: the *reuse* of concrete pieces – sourced from the deconstruction of buildings or infrastructure – into new projects. By carefully dismantling pieces and reassembling them in new projects, reuse aims at retaining the intrinsic values of the reclaimed material, with little to no reprocessing. Reuse is therefore usually a strategy to prioritize over recycling. Because it prolongs the service life of existing products, reuse reduces the demand for new ones and waste generation.

1.2. Reuse of concrete pieces in new construction projects

The reuse strategy is recognized by the International Energy Agency as a key research axis for greater material efficiency (IEA, 2019). As load-bearing materials account for the largest share of embodied greenhouse gases in buildings (Hoxha et al., 2017; Röck et al., 2020), their reuse (3rd circular strategy) potentially allows for the highest environmental benefits, as already measured by several built projects and simulation studies (Gallego-Schmid et al., 2020; Küpfer et al., 2021).

Obsolete buildings are often structurally sound prior to their transformation or demolition, and the same is true for their load-bearing components once extracted. Indeed, buildings, especially in urban areas with high land pressure, are typically demolished for reasons unrelated to material grade and structural performance (Abramson, 2016; Ashby, 2013; Salama, 2017). Their load-bearing systems are generally well protected from weathering during their service life, and their components – mostly concrete – could be used longer, that is, reused in new projects.

Before industrialization, reusing stones, bricks, or timber was a common practice because extracting and manufacturing new components was relatively more expensive and time-consuming (Addis, 2006; Barles, 2014). Today, structural component reuse is seldom considered despite a growing number of convincing applications, published both in scientific journals (Brütting et al., 2019; Gorgolewski, 2008) and practice-based books (Addis, 2006; Allwood et al., 2012; Choppin et al., 2014; Küpfer and Fivet, 2021; Stricker et al., 2021). These advertised applications however mainly concern reticular structures made of salvaged steel or timber.

Applied to concrete structures, component reuse, shown in red on Fig. 1, consists of: carefully separating obsolete structures into pieces of relatively large sizes, using, for example, a diamond saw, Fig. 2a, or high-pressure water jets; and reassembling the pieces in another structural project without significantly altering their geometric and mechanical features, Fig. 2c and d.

Early studies on the Piecewise Reuse of Extracted Concrete in new Structures (PRECS) demonstrate simultaneous reductions of waste generation, raw material consumption, and greenhouse gas emissions (Glias, 2013; Küpfer et al., 2022; Roth and Eklund, 2000). Moreover, the formal and mechanical characteristics of salvaged components, the marks of their past use, the original craft, and, more broadly, their embedded technological value, are recovered as much as possible across new service cycles (Addis, 2006; Choppin et al., 2014). However, PRECS also involves known risks related to the uncertainties of unconventional supply chains and pioneering construction approaches (Huuhka et al., 2019). It also requires additional design work for connection details (Widmer, 2022) and new types of material quality assessment (Devènes et al., 2022a).

1.3. Levels of reuse

A distinction is made between three levels of value recovery through concrete-component reuse, depending on the difference between the structural requirements for the components in the new design solutions and those in the donor structure:

- When requirements for the components are globally comparable in both structures, the recovery level corresponds to an *equivalent* reuse, Fig. 3a.
- When requirements are lower in the receiver structure, the reused components are downcycled. *Downcycling* reuse typically happens when the reused components are subject to a smaller variety of loads or stresses or to smaller magnitudes of said loads or stresses. For instance, in Fig. 3c, sawn cast-in-place reinforced concrete slab pieces are reused as parking pavement, which means that the flexural strength provided by the reinforcement bars is no longer valued to its full extent.

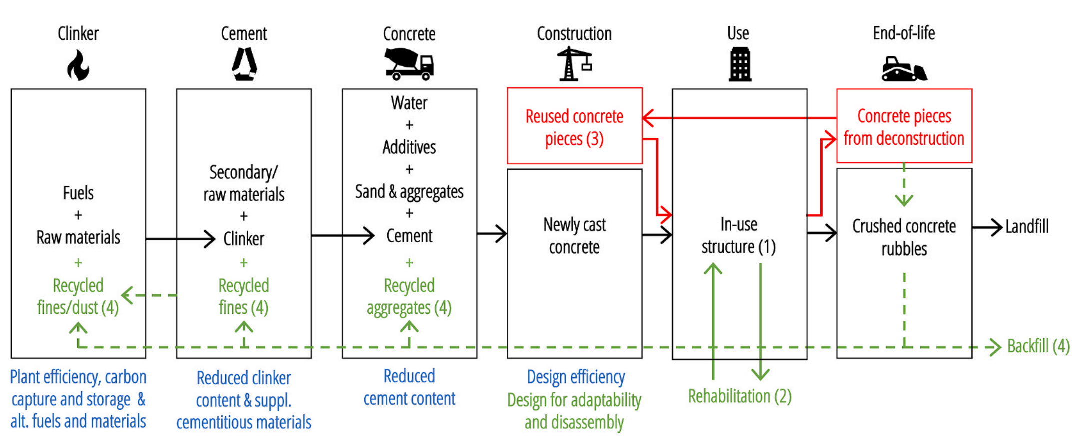


Fig. 1. Concrete value chain. In black, conventional concrete production and service cycle. In colors, strategies to lower the DEI of concrete: direct strategies in blue, circular strategies in green, circular reuse strategies in red. Numbers indicate the circular strategy priority to lower DEI. Adapted from (Habert et al., 2020).

Fig. 2. Concrete-reuse process: piece sourcing through deconstruction (a,b), preparation, storage (c), and reassembly (d) in the new project. Image credits: (a, c, d): FAZ Architectes; (b): Ingeni SA.

Fig. 3. Levels of concrete reuse: example of equivalent reuse of slabs as slabs in C31 (a), downcycling reuse in C68 (b), and upcycling reuse in C54 (c). Image credits/ sources: (a): (Heyn et al., 2008b); (b,c): EPFL/Küpfer.

- When requirements are higher in the receiver structure, the reused components are upcycled. *Upcycling* reuse typically relies on structural reinforcement or on a combination of components. For example, in Fig. 3b, two precast slabs previously simply supported are sandwiched together to allow for cantilevered use.

When pursuing a high resource efficiency strategy, the inherent capacities of salvaged materials should be reused to the maximum extent. Therefore, *equivalent* and *upcycling* reuse should – when matching the project brief – be preferred over *downcycling* options, and, if downcycling is unavoidable, its extent should be minimized.

1.4. Existing literature on the PRECS strategy

PRECS is a little-known strategy outside the territories where it has been practiced, and knowledge on it is fragmented. The extent and diversity of design solutions involving PRECS are only partially described. No comprehensive overview of the practice diversity and history has been found in the literature. In addition, the technical, environmental, economic, logistical, and design implications often remain documented in isolation. Indeed, in the few existing studies, the data are typically bound to one project or similar projects belonging to a geographically or typologically similar set of solutions. For example, Heyn et al. (2008b) collected technical, logistical, economic, and environmental data that focus on the reuse of precast concrete panels from East Germany in new low-rise buildings before 2010. Küpfer et al. (2022) documented and analyzed two recent projects reusing concrete pieces reclaimed from cast-in-place concrete structures in Switzerland. Bellastock (2018) analyzed two wall systems that reuse sawn precast panels in France. Al-Faesly and Noël (2022) surveyed perceived barriers to concrete reuse among concrete industry professionals in Canada. Two of the rare studies that combine diverse practices are the work of Salama (2017) and Huuhka et al. (2019). The first work introduces three projects, all built with precast panels but in three countries, and briefly identifies some of the challenges of PRECS. The second discusses four projects, all built with precast panels, but of different sizes, in different decades and in four countries. Overall, a comprehensive overview of the diversity of design solutions, history, benefits and limitations of this strategy is lacking to properly inform researchers, designers, real-estate owners, construction companies, and policy-makers.

1.5. Goals and contribution

While PRECS is a little-known strategy and its documentation is fragmented, this paper aims at testing the following three hypotheses:

(1) built precedents of PRECS have existed for many years or decades;
(2) a large diversity of proven PRECS solutions is readily available;
(3) barriers to broader adoption can be inferred from existing documentation and are largely transitional.

Therefore, this study provides an unprecedented critical review of hitherto fragmented documentation and industry experiences. Overall, it is demonstrated that concrete component reuse is a practice that already has a long history and a number of successful operations in terms of environmental impact and cost, hence further supporting its potential to become a more widespread means of cleaner construction. The main scientific contributions of this study include:

(1) the construction of an original database of 77 PRECS projects designed between 1967 and 2022 in Europe and the U.S.A.;
(2) the identification of seven PRECS trends whose practices span three periods since 1967, introducing a new perspective on the history and design possibilities of PRECS;
(3) a critical review of the state of knowledge on the supporting forces, persistent constraints, and transitional barriers of PRECS, and the identification of future research priorities.

The article is organized as follows. The scope of the study is presented in Section 1.6. Section 2 describes the three-phase methodology of the work. The collected literature and case studies are introduced in Section 3. Results of the diachronic and synchronic analyses are presented in Sections 4 and 5. The limitations of the study, barriers to overcome, societal relevance, and future research priorities are discussed in Section 6. Section 7 concludes the study.

In this work, the term *case study* refers to a specific construction project, built or projected, with its own extraction and reassembly techniques. The terms *practice* and *trend* refer to a subset of *case studies*, with common geographical, historical, cultural, architectural and/or technical features. The term *strategy* refers to the general concept of PRECS. Finally, the term *donor* structure refers to the obsolete existing structures from which components are extracted. The project in which the components are reused is referred to as the *receiver* project.

1.6. Scope definition

The study focuses on the reuse of extracted concrete pieces in new structural assemblies, as detailed in the following paragraphs.

Pieces reuse, not adaptive reuse: The study focuses on solutions that require the dismantling of parts to be reused and their subsequent reassembly. Transformation/renovation/retrofitting solutions in which concrete remains in place and is not dismantled, even when the program changes, are typically grouped in the so-called *adaptive reuse* (Wong, 2016) design strategy and are out of scope.

Component reuse, not recycling: The study focuses on solutions where the concrete does not undergo a recycling process between the extraction step and its next use in the new construction project. Often confused, component reuse is different from material recycling: when reused, the concrete pieces are not crushed but directly reused without major change in the physical composition of the material. Nevertheless, cleaning, sawing, reconditioning, reinforcement, and preparation of connections are part of the reuse strategy.

Existing concrete, not new concrete: The study focuses on the valorization of concrete that is already present and used in the built environment. Therefore, design solutions that, to achieve future reuse, first rely on the manufacturing of new components and the pouring of new concrete, are out of scope. These solutions are typically included in the design strategy called *design-for-reuse* or *design-for-disassembly* (Crowther, 1999). The study also excludes the use of leftover ready-mix concrete and unsold new precast concrete pieces.

Requalification of discarded and unwanted concrete components, not an additional use of existing designed-for-multiple-use products: The study focuses on the revalorization, requalification, or repurposing of concrete pieces that would be discarded if no design efforts were made to reuse them. Consequently, the reuse of pieces expressly designed to be used multiple times is out of scope unless they are reused differently than initially planned. An example of such pieces is stackable counterweight concrete blocks designed to be moved from one site to another. The reuse of small independent concrete objects easily movable as a whole (like washbasins or flower pots) without additional design effort and for the same function is also not part of the study. Design-for-disassembly concrete solutions, as described in the previous paragraph and such as those developed by Peikko (Paananen and Suur-Askola, 2018), are also considered design-for-multiple-use products when reused for the same use as planned and thus excluded from this study.

Structural assembly: Since load-bearing structures are responsible for most of the embodied energy of buildings, the study only addresses design solutions where stresses are transferred between assembled pieces and where the behavior of the structural assembly must be specifically checked, such as building and bridge structures, or road, hydraulic and agricultural engineering works. Landscape design elements, like stepping stones, low garden walls, self-supporting facade cladding, small outdoor equipment like benches, sculptural objects, small furniture and wall cladding are excluded from this study.

Component composition: Both precast concrete components and cast-in-place concrete structure parts are considered in this study. Precast concrete components are produced in a factory before being transported and assembled on the construction site. A structure made of precast components is characterized by several visible or hidden joints. For cast-in-place concrete structure, the concrete is molded onsite using formworks, usually creating a monolithic structure.

The combination of concrete with another material in the extracted pieces is not an exclusion criterion. Concrete can typically be combined with steel beams in existing composite slabs or insulation for existing facade sandwich walls. The combination of reclaimed concrete pieces with new components made of another material is also included in the research. Finally, in this study, concrete refers to modern concrete with Portland clinker, usually reinforced with steel bars.

Built and unbuilt projects: The study includes built and unbuilt examples. Projects that have been designed but not built proved useful in documenting PRECS characteristics.

2. Methodology

2.1. Overview

The study follows a three-step methodology, summarized in Fig. 4. Phase 1 is the data collection of PRECS practices, the identification of case studies, and their documentation. During Phase 2, case studies are chronologically analyzed and compared. Practice trends – i.e. groups of case studies with geographical, technical and/or typological similarities – are identified. During Phase 3, records are analyzed to detect opportunities, challenges, impacts, and constraints specific to the PRECS strategy, as well as research gaps. The following sections provide methodological details about the three phases.

2.2. Data-collection search method (phase 1)

Data collection starts by assembling published records on PRECS and ends with the identification of all documented case studies. Published records are first sought in four scientific databases: Scopus, Web of Science, ProQuest, and Swiss Library Service Platform. The search query is set for all fields as follows: "concrete AND salvag* OR reclaim* OR reus* OR re-us* OR repurpos* AND architect* OR build* OR construct* OR design*". For each database, the first 800 results by relevance order are checked. The search is limited to items searchable in online databases as of May 2022.

Additional records are sought through Google and YouTube searches, using the same list of keywords. Since case studies are typically documented locally, additional queries are performed in the local languages of identified research projects and case studies. A search on social networks is also performiked to detect other potentially recently documented solutions. The record collection (Appendix A) is finally supplemented with references cited in records collected until then.

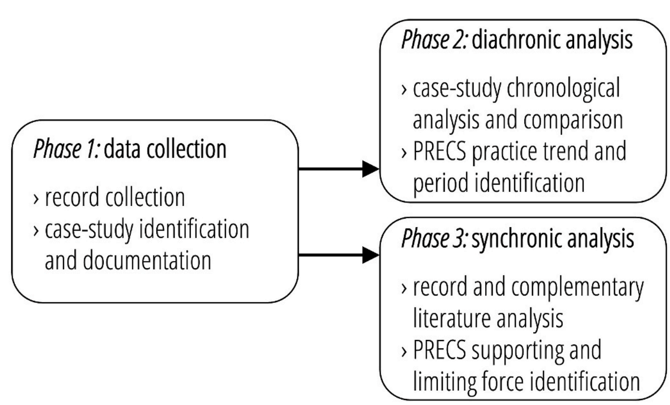


Fig. 4. Methodological framework.

Original case studies – i.e. unique design solutions involving PRECS – matching the study scope are identified by carefully reading all collected records. They are then chronologically numbered and described in a table (Appendix B). For case studies with little documentation, efforts are made to search additional records to further document them.

2.3. Diachronic analysis method (phase 2)

In Phase 2, a diachronic analysis of the case studies is conducted. This analysis aims to understand the diversity of PRECS practices and how they changed over time. A graphical representation on a timeline – later presented in Section 4.1. – is developed to support the visualization of the multiple and multifaceted characteristics of the case studies. Similarities and differences in key characteristics of the case studies are then identified based on a historical, geographical and technical cross-reading of the graphical timeline, the case-study table and the records. Through an iterative process, clusters of case studies with several similarities are detected. Projects reusing the same type of concrete components, in a defined geographic area, for buildings of the same size, are typically grouped and form trends in PRECS practice. Key periods of change are additionally detected from the graphical and literary material, and the chronological comparison of trends.

2.4. Synchronic analysis method (phase 3)

In Phase 3, a synchronic analysis of PRECS strategies is conducted. The analysis consists in extracting recurrent causes and implications on architectural and engineering projects and on the economic, social, and environmental dimensions of sustainability. The analysis is first performed manually from the collected literature, lessons from the case studies and complementary technical literature. Results on individual sources are then critically compared to each other and (re)combined through an iterative process. They are eventually organized into five themes: (1) technical aspects, (2) economic aspects, (3) environmental implications, (4) project-management and supply-chain aspects, (5) design and socio-cultural values. These themes cover all dimensions of sustainability and circular economy as well as areas specific to construction, namely technical, cultural, and design aspects. For each theme, defining characteristics are divided in two groups: supporting forces, such as drivers, benefits, and opportunities for the involved persons or goods; and limiting forces, such as constraints, bounds, and risks for the involved persons or goods.

3. Collected literature and case studies

3.1. Literature corpus overview

The records collected are presented by type and publication year on Fig. 5. It includes eight journal articles, eighteen conference papers and presentations, ten books or book chapters, sixteen theses, eighteen reports or factsheets, and twenty magazine articles, interviews, webpages or videos (see Appendix A for the complete list).

The earliest collected records date from the 1980s and the 1990s and were found in books, book chapters and architecture magazines. They discuss early experiences with the reuse of precast pieces in mainly industrial projects in Germany (see Section 4.2) and of precast panels in large-scale housing projects in the Netherlands and Sweden (see Section 4.3). The first record focusing on the reuse of cast-in-place concrete components (Roth and Eklund, 2000) dates from 2000, and marks the beginning of series of scientific publications on PRECS during the 2000s.

In general, the frequency of identified records increases over time. For the most recent years, seven journal articles and conference papers and eight Master theses published since 2020 are collected, suggesting current academic interest.

3.2. Case-study corpus overview

Appendix B (see Section 2.2) lists the case studies collected. The corpus is not exhaustive, as not all design solutions are published in publicly-available records and due to inherent limitations of the search. In addition, levels of data availability, clarity, and reliability are uneven. Fig. 6 plots the number of case studies according to their location (a),

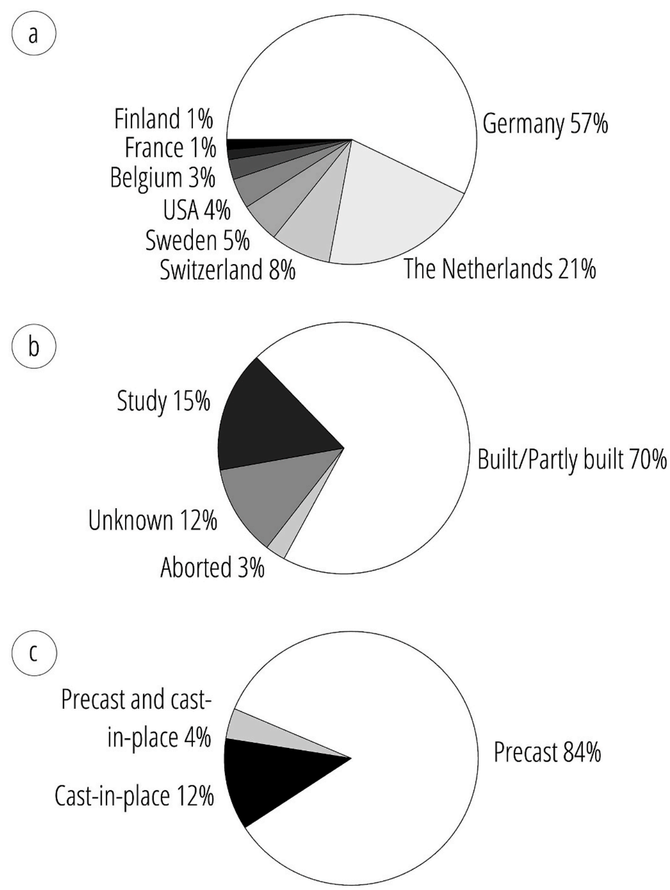


Fig. 6. Distribution of identified PRECS case studies per country (a), status (b) and concrete fabrication type (c).

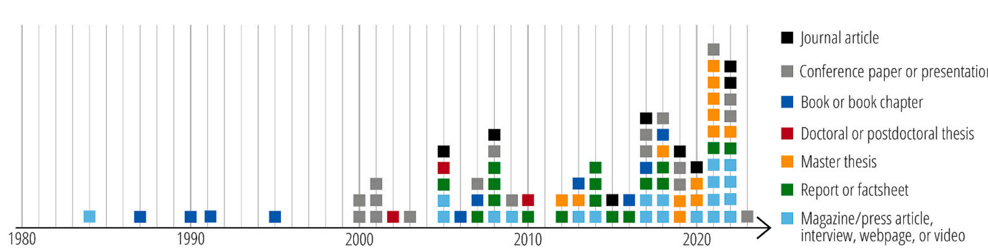


Fig. 5. Collected records by publication year. Record references are available in Appendix A.

construction state (b), and concrete type (c). In total, 77 documented design case studies are collected. Among them, 54 are built projects. Nine case studies have uncertain construction status, their construction having been planned but not confirmed in publications. Two construction projects have been aborted, either for coordination and economic reasons, or for reasons independent of the project. Twelve design case studies are not built because they were never intended to be built in the near future. They are mostly preliminary or feasibility design studies stemming from Master theses. The 54 built projects were erected between 1967 and 2012. Among them, 53 are in Europe, mostly in Germany, and one in the USA. The built projects identified include large multi-story apartment buildings, low-rise buildings, pavilions, and

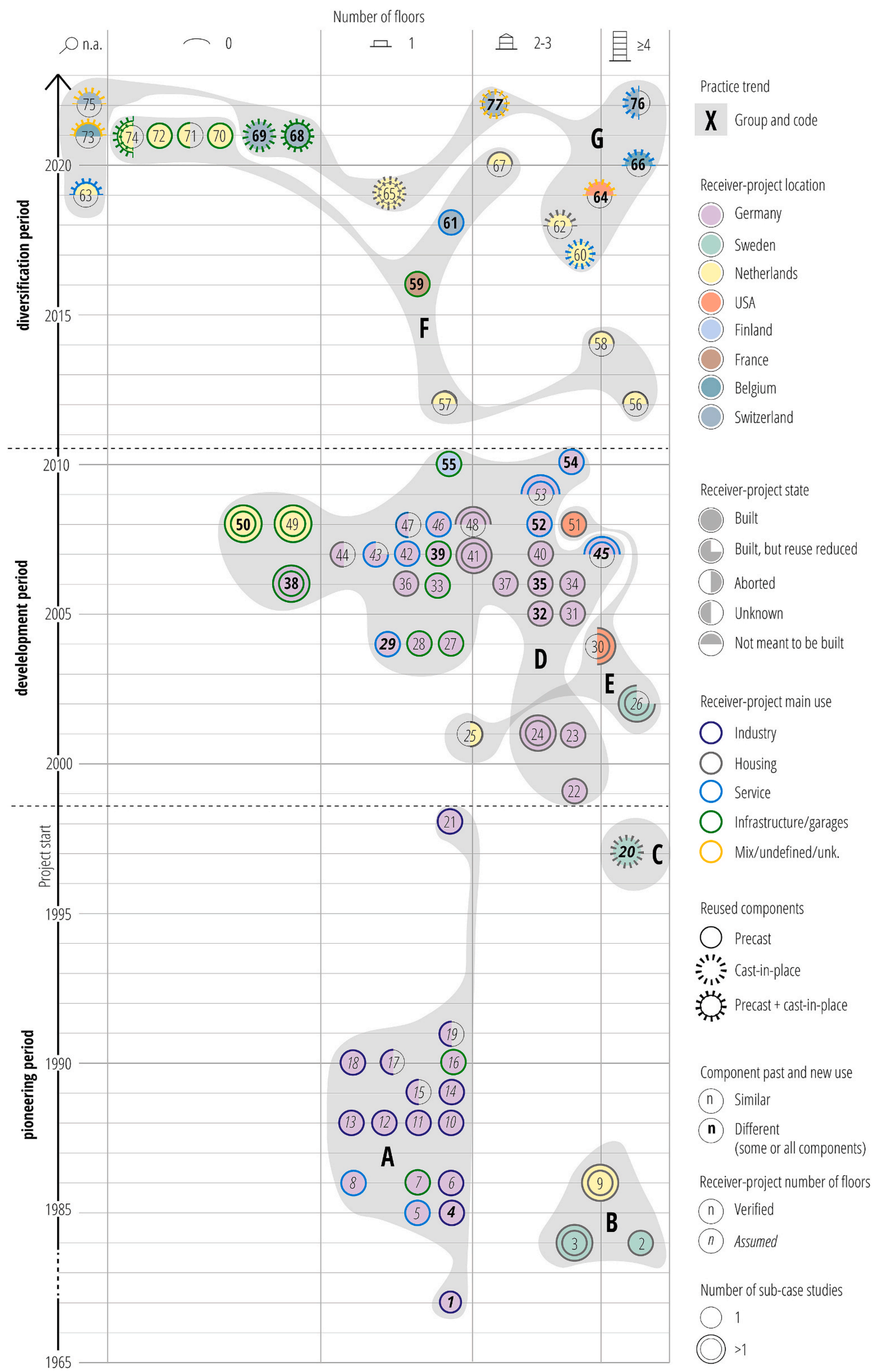


Fig. 7. Timeline of collected case studies. Each case study is represented by its number, as listed in Appendix B, and included in a practice trend, as summarized in Table 1. Case studies between two floor-number categories include buildings of both floor numbers.

infrastructure work. Reused concrete components include mostly precast panels from mass housing buildings with or without dimensional change, but also other precast components or pieces of concrete extracted from monolithic structures ranging from small blocks to large pieces. Nonetheless, despite the existing variety of built projects, the overall number of identified built precedents confirms that PRECS is currently limited to the status of a niche practice.

4. Diachronic analysis: development trends

4.1. Overview

The diachronic analysis introduces a new perspective on the history of PRECS practices. It traces back the diversity of precedents and highlights changes in the scale of applications e.g. between small-scale pavilions and multistory buildings, in the function of donor and receiver buildings, in the type of original concrete construction method (precast or cast-in-place), in countries of application, and in the nature of operations e.g. between large-scale construction projects and academic experiments. As summarized on Fig. 7 and Table 1, the analysis detects (1) seven chronological trends that group case studies with similarities in reuse technique and project type and (2) three main time intervals:

- the early, pioneering period from 1967 to 1998, with trends A, B, and C;
- the intermediate, development period from 1999 to 2010, with trends D, and E;
- the recent, diversification period from 2011 to 2022, with trends F, and G.

Table 1 summarizes the key characteristics of the seven trends. The main criteria are location, type of reused concrete component, size of receiver-project (number of floors), use of donor and receiver projects, and project state. Case studies from a same trend stem from common drivers and typically arise from a comparable built and socio-economic context. Resulting from this analysis, the following sections chronologically detail the specificities and lessons learned from each of the seven trends.

4.2. Early reuse of precast concrete components in Germany (trend A)

The first detected PRECS trend refers to the early practice of reusing precast concrete pieces in low-rise buildings, mainly from and into industrial sites in Germany from 1967 until 1998. The earliest case study (C1) is the overall earliest PRECS case study identified in this research. Sixteen other case studies reusing precast components in 1-story buildings in Germany are identified (C4–C8; C10–C21) (Fischer et al., 2012; Mettke, 1995, 2017). In most cases, the distance between the donor and receiver projects is short when not on the same site or coinciding. Consequently, this practice seems driven by a pragmatic use of locally available resources.

Various types of precast components are reused, often for *equivalent* reuse, Fig. 8c and d. For example, depending on the case study, wall panels, roof panels, trusses, purlins, and columns are dismantled and reused for the same function, mainly without resizing or major changes in the assembly system. In one case study (C16), roof panels are reused in a new roof with higher loads than in the donor building, but calculations have verified that the loading capacity was large enough.

In some cases, components are reused for a different function. For example, precast slabs of a 6-story building are reused to stabilize the floor of a new plant (C1), wall panels of a gym hall are reused as ground floor reinforcement in an industrial building (C4), and columns are reused as strip foundations (C11).

Table 1
Main specificities of the seven practice trends detected through the diachronic analysis.

period	1967–1998			1999–2010		2011–2022	
	pioneering period			development period		diversification period	
practice trend	A early reuse of precast concrete components in Germany	B first large-scale experiments reusing precast concrete panels	C pioneering reuse of cast-in-place concrete for like-for-like applications	D research and application reusing German mass-housing precast concrete panels in low-rise projects	E aborted large-scale projects reusing precast-concrete components	F diversification of precast concrete reuse	G new applications reusing cast-in-place concrete pieces
							
total number of case studies (including built ones)	17 (14)	3 (3)	1 (1)	30 (25)	4 (2)	10 (4)	12 (5)
location	D	S, NL	S	D (NL, F)	NL, S, USA	Europe	Europe, USA
number of floors	1	2–7	unknown	0–3	2-4; unknown	various	various
receiver building main use	industrial	housing	housing	housing, service, infrastructure	housing, mixed	various	various
donor building main use	industrial	housing	housing	housing	infrastructure, housing	various	various
main external appearance of concrete	unknown, hidden	hidden	unknown	hidden	unknown, visible	visible	visible
concrete main type	precast	precast (panels)	cast-in-place	precast (panels)	precast	precast	cast-in-place
record overall quality	low	high	low	high	variable	variable	variable

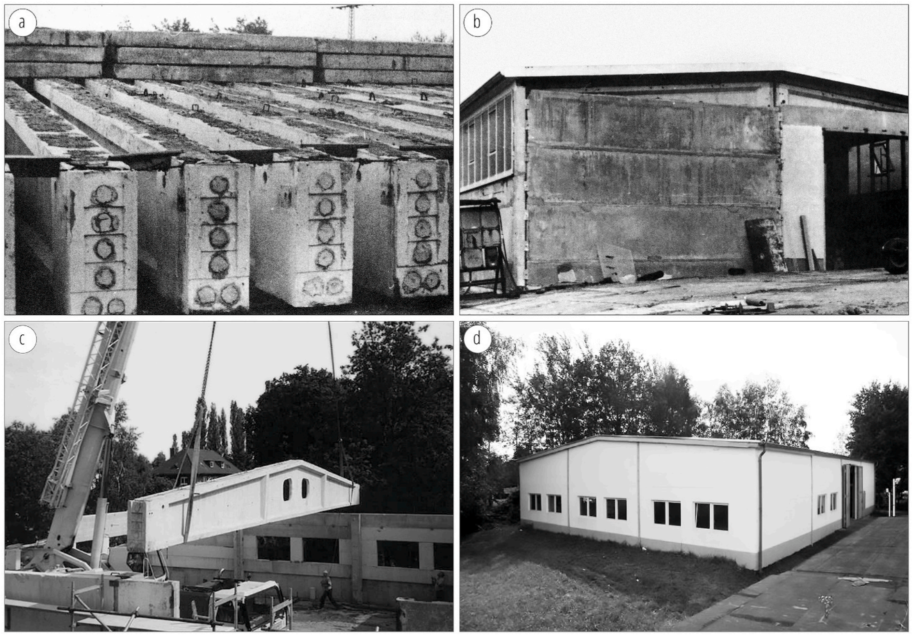


Fig. 8. Reuse of precast components in German industrial sites: in Bärwalde (D) (C13– C15, C18–C19) between 1980 and 1990 (a,b), and in Lauchhammer (D) (C21) in 1998 (c,d). Image credits/sources: (a,b): Mettke (Mettke, 1995); (c,d): Mettke (Mettke, 2017).

4.3. First large-scale experiments reusing precast-concrete panels (trend B)

Trend B is another pioneering PRECS approach. It refers to the early reuse of precast concrete panels in large-scale housing buildings in Northern Europe in the 1980s. Three built case studies located in Sweden (C2, C3) and the Netherlands (C9) are identified for this trend. Their components are only 14–16 years old when reused into 2-, 3-, 4- and 7-story housing buildings. Components are typically salvaged from the upper floors of mass-housing buildings that are leveled down for socio-economic reasons. Their reuse is eased by the limited adhesion of the precast-system connections (Huuhka et al., 2019). These case studies are believed to be the first to apply PRECS reuse on multistory buildings.

Dating from 1984, the scale of case studies C2 and C3 is still unrivaled despite being the second oldest collected case studies. Without prior comparable experience, 320 new dwellings are built reusing precast panels salvaged from facade walls and slabs (Gieselmann, 1991; Huuhka et al., 2019; Irion and Sieverts, 1984; Nagora, 2002). Thanks to hooked connections in the precast system, panels are easily disassembled and taken to a disused prefabrication factory for cleaning. About 80–85% of the panels are deemed reusable and reclaimed to build a 7-story apartment building (C2), Fig. 9c and three sets of low-rise houses (C3), Fig. 9b, all located within a radius of 20 km of the donor buildings. The support by the precast-system developer during the

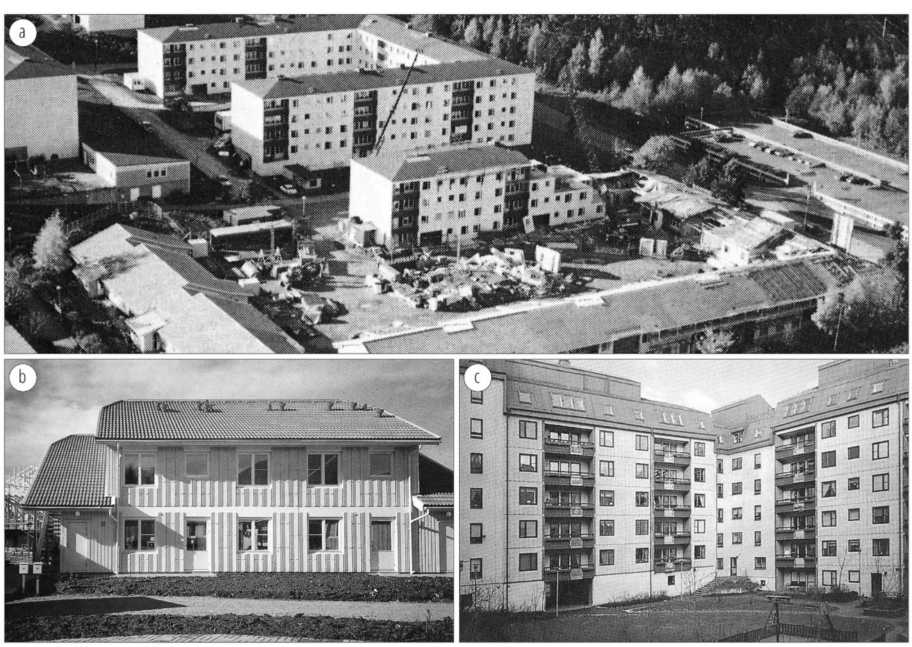


Fig. 9. Illustrations of C2 and C3 in Gothenburg (S), 1984. High-rise buildings are leveled down (a). Salvaged components are used to build row houses (b) and a 7-story infill building (c). Image credits/sources: (a): B. Baldursson (Mühlestein, 1987); (b,c): (Gieselmann, 1991).

deconstruction and reassembly phases of the project contributed to the technical success.

Along with C9 where nine hundred precast panels are reused (Coenen et al., 1990; Huuhka et al., 2019; Naber, 2012; te Dorsthorst et al., 2000), Fig. 10, these pioneering projects demonstrate early on the technical feasibility of reusing concrete panels into large-scale, multi-level housing projects. In (Irion and Sieverts, 1984), the authors report a plan to ship some of these panels to Arabia, to build additional low-rise houses. While one might question the economic feasibility and environmental relevance of this proposal, no record has been found to confirm the execution of this plan.

4.4. Pioneering reuse of cast-in-place concrete for like-for-like applications (trend C)

In 1997, the Swedish "Udden project" (C20) pioneers the reuse of cast-in-place concrete parts that are sawn prior to be reassembled with new connections (Addis, 2006; Eklund et al., 2003; Roth, 2005; Roth and Eklund, 2000; Salama, 2017), Fig. 11. 1′850 tons of large concrete wall elements, floor beams and foundations from two donor buildings are reused in a new 26-apartment building located 64 km away. In the collected records, no technical issue is reported, supporting the technical feasibility of reusing cast-in-place concrete pieces for multi-housing buildings. An environmental analysis shows that the reuse of the components saves, in this case, 60% of CO_2 emissions and 40% of energy use when compared to a similar building made of new concrete (Roth and Eklund, 2000). Costs are 10–15% higher than conventional practice, compensated by a governmental grant for new sustainable building practices. Nonetheless, according to Eklund et al. (2003), contractors are optimistic that a 10–15% cost reduction could be accomplished in the future for similar reuse applications, thanks to gained experience and knowledge on larger scale projects.

4.5. Research and application reusing German mass-housing precast concrete panels in low-rise projects (trend D)

The year 1999 in Germany starts a period of prolific research and construction activities related to the reuse of precast concrete panels from obsolete mass-housing buildings in new low-rise projects. In total, 30 design projects, mostly single-family or multi-family houses but also garages, association houses, agricultural equipment like low silos and storage, and research prototypes like exhibition pavilions and dikes, are identified. At least 25 are built between 1999 and 2010, Fig. 12. Many of them are listed (Dechantsreiter et al., 2015; Fischer et al., 2012; Heyn et al., 2008b) and accompanied by researchers from BTU Cottbus, and TU Berlin.

Most panels are salvaged from socio-economically obsolete East-German mass-housing buildings dating from the late 1960s to the late 1980s. Using locally available resources, the design solutions reuse components from several precast concrete-panel systems. In general, their reuse leads to important cost and environmental impact reductions. For example, Asam (2007a) estimates the economic savings to reach 26% in case of optimal reuse of the panels. Late case studies in this trend are the first one to leave the reused concrete exposed (e.g. C29, C52, C54).

At the beginning of this period, reuse mostly presents equivalent requirements between donor and receiver buildings. The first housing and garage projects reuse wall and/or slab panels for the same function (e.g. C22–C24, and C33). Original connections and dimensions of the panels are typically preserved and influence the design of the projects. This PRECS practice is later replicated in Finland with locally salvaged panels (C55) (Hagan, 2013; Hagan and Kontukoski, 2009; Huuhka et al., 2019). In some cases, the structure is reinforced, for instance with wooden beams (C28) (Mettke, 2010).

In 2004, resized panels that have lost their original details are reused in a research pavilion (C29) (Asam, 2005, 2007a, 2007b; Fischer et al., 2012). New assembly systems and reinforcement techniques are devised, such as carbon lamellae, and reversible connections using post-installed steel anchors, which allows the pavilion to be – at least once – dismantled and reassembled in another location. Learning from this experiment and the developed construction details, other projects later reuse panels in a function different from the one they had previously. For example, reclaimed slab panels are reused as walls for a 2-story-high atrium and cut wall elements are reused as roof-pitch elements and ridge beams (C32). Different jointing techniques are also tested to reuse panels in dike prototypes (C38). In another pavilion later

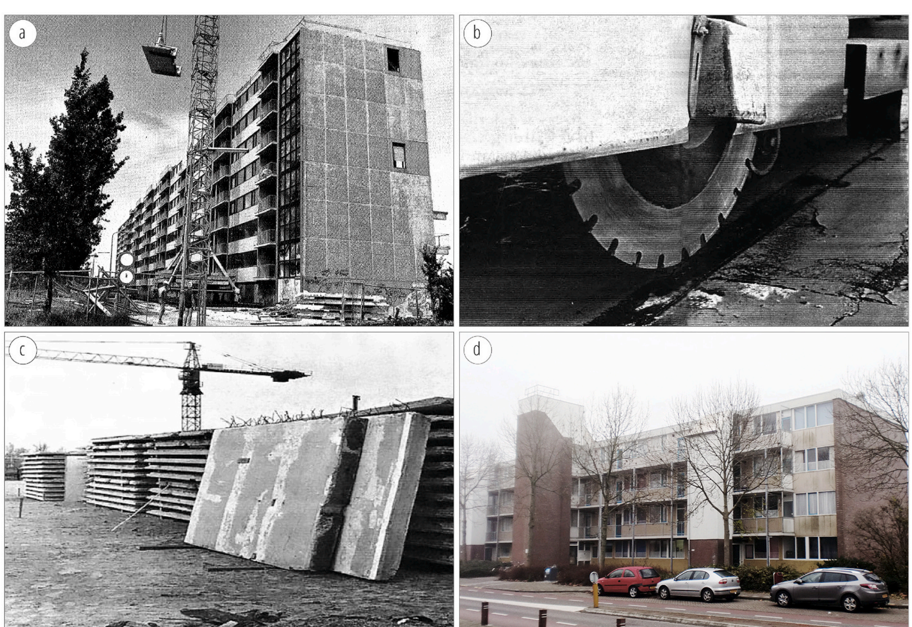


Fig. 10. Illustration of C9 in Middelburg (NL), 1986. Careful dismantling of the top 7 floors of a 11-story precast building with sawing and lifting equipment (a–b). Salvaged panels (c) are used to build 3- and 4-story apartment buildings (d). Image credits/sources: (a) De Delta (Naber, 2012); (b,c) CIB (Kristinsson et al., 2001); (d) Nanda Naber (Huuhka et al., 2019).

Fig. 11. Illustration of C20, 1997: donor building in Finspång (S) (a) and receiver-project construction in Linköping (S) (b). Image credits/sources: (Eklund et al., 2003).

Fig. 12. Selection of case studies reusing precast panels from Germany: completed house (C22), 1999 (a); residential project (C24), 2001 (b); and garage (C33), 2006 (c); under construction dike prototype (C38), 2006 (d); and house (f), with its donor building (e) (C36), 2006. Image credits/sources: (a,b) Mettke (Heyn et al., 2008b); (c,d) (Heyn et al., 2008b); (e,f) WK21 (Kil, 2007).

built in 2010 (C54), complexity is added to the design by combining panels from two precast-panel systems and upcycling slabs working as simple beams into cantilever slabs: the two slabs are superimposed placing their reinforcement bars on the outer sides and connected like a sandwich panel with post-installed rebars and new concrete. In 2022, the pavilion is still in use in Berlin (D) and a visual inspection by the authors confirmed the overall good condition of the concrete structure. The combination of the two precast systems has cultural and historical importance as plates come from both former East Germany and West Germany (Dechantsreiter et al., 2015; Fischer et al., 2012; Vogdt et al., 2016).

4.6. Aborted large-scale projects reusing precast-concrete components (trend E)

At the beginning of the 21st century, some European and American large-scale projects planned to reuse precast concrete pieces but remained partly or fully incomplete for reasons depending on the project or independent from it. Three projects not fully built or aborted are identified in the 2000s.

In the Nya Udden project (C26), the original project includes about 500 apartments. At first, 54 flats are built reusing four hundred precast wall, beam and staircase components, but the remaining flats are later built using conventional techniques. No major technical issue related to the construction involving reused components is reported. Steel beams are added to reinforce the structure and a solution is found to solve the system insufficient acoustic and thermic performances. However, the fact that different contractors are responsible for deconstructing and reassembling the reclaimed components is believed to be a key cause for the interruption of the reuse process. "*This led to delays, lack of overall coordination and difficulties with storage of the goods between deconstruction and reuse – the firm deconstructing the elements had little incentive to handle them carefully and ensure they were not damaged.*" (Addis, 2006). Finally, the flats with reused components are reported to be 10–15% costlier than ones built with conventional construction (Addis, 2006; Eklund et al., 2003).

Aborted around 2001, the Maassluis project (C25) – which initially planned on reusing precast components of six housing buildings in the Netherlands – illustrates other barriers of concrete reuse. te Dorsthorst et al. (2001) report that one key contributor to the abortion of the project is the late discovery that the connections had not been built as drawn. This late discovery complicates the deconstruction process and requires additional safety measures. One can deduce that the project lacked buffer time to reconsider and adapt the deconstruction method.

The Big Dig Building (C30), a large mixed-use housing project designed to reuse the concrete and steel structural components salvaged from provisional highway ramps built in Boston (USA), is stopped because of the sudden loss of the main architect (Gorgolewski, 2017). The project however later provides the necessary impetus for constructing a house (C51), Fig. 13, where 270 tons of materials are reused: steel columns and beams and precast bridge-deck elements consisting of a concrete slab over steel beams (ArchDaily, 2009; Gorgolewski, 2017). Design implications of infrastructure component reuse are multifaceted. For example, because of the geometry of the ramps, the panels have a slightly trapezoidal shape which results in the house having few right angles. Additionally, the panels have a high load capacity – about six times that of a housing project – and long spans. Therefore, the house design takes advantage of these features by adding a highly-vegetated roof and striving for programmatic freedom of the space that may imply higher load cases in the future. However, the full capacity of the reused components is not used, and the process might be referred to as a *downcycling* reuse. Finally, since only minor sawing and drilling operations and limited new connection preparation are required, construction costs and time are reduced compared to conventional construction methods (Gorgolewski, 2017).

4.7. *Diversification of precast concrete reuse (trend F)*

During the 2010s and the beginning of the 2020s, theoretical research and built solutions expand the scope of design possibilities of PRECS with precast components. The geographic area in which these solutions are being studied is also extended – with initial work on structural concrete reuse identified in France (C59), and Switzerland (C61).

New types of components appear for the first time in the collected case studies. For example, garden tiles are upcycled in new self-standing walls (C61, Fig. 14d) (Borges, 2022; Meyer, 2018), train-station platform tiles are reused as large courtyard pavement (C72, Fig. 14c) (Hof van Cartesius, 2021) and hollow-core slabs from an office building are studied to be reused in new housing projects (C56–C57) (Naber, 2012). The like-for-like reuse of bridge girders in new bridges is explored in the Netherlands (C70–C71, C74, Fig. 14a) (Arc2 architecten, 2021; Implenia, 2021). Vergoossen et al. (2022) recommend reusing precast bridge girders without removing the cast-in-place slab on top if in a good state, which would limit construction waste production and material and energy consumption.

New assembly methods are also tested, in addition to those applied in the past for some types of precast elements. For example, Bellastock develops two new wall systems made of sawn pieces of precast panels that thus have lost their original connections (C59) and require new connections (Bellastock, 2021; Bellastock, 2018), Fig. 14b.

Drivers of these new design solutions are related to different aspects of sustainability. For example, Bellastock values the environmental and potential economic savings but also underlines the new distribution of costs, which favors local employment over new material import (Bellastock, 2018; Chantereau, 2017). Besides, the work of Glias (2013), another study on the environmental benefits of reused concrete, is published in 2013. For a project in the Netherlands, the study concludes that the DEI of a structure composed of reused precast elements can be reduced by 75%. Based on promising results accumulated so far, new research projects on the entire precast-concrete reuse value chain, such as the European-funded ReCreate research project (European Commission, 2022), are launched to help the European Union achieve its climate goals.

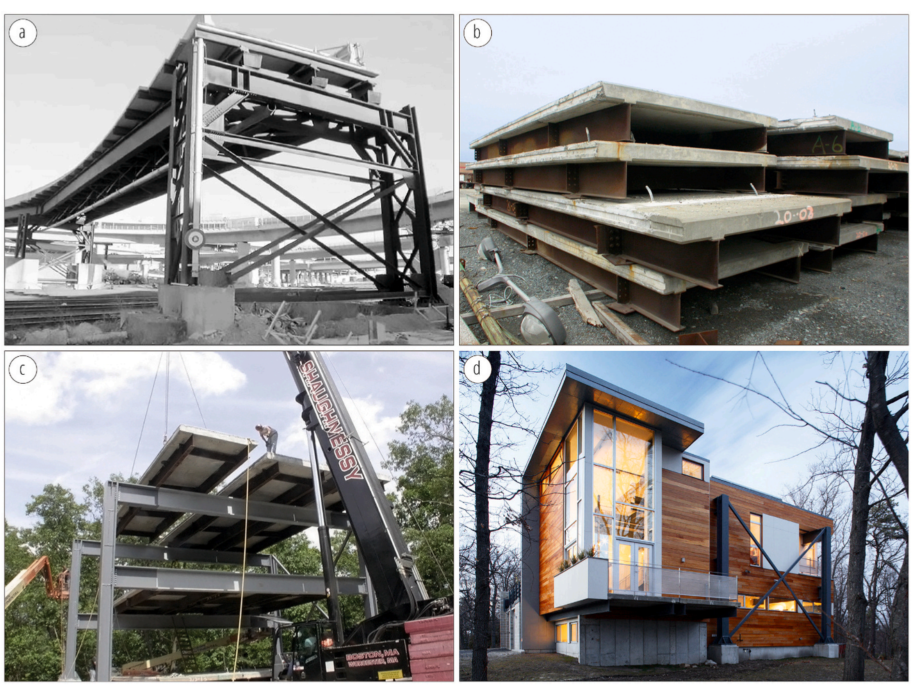


Fig. 13. Concrete-steel bridge-deck elements (b) and steel profiles salvaged from a temporary elevated highway (a) are reused in a housing project (C51), 2008 (c,d). Image credits/sources: John Hong/SsD (published in (ArchDaily, 2009) and (Gorgolewski, 2017)).

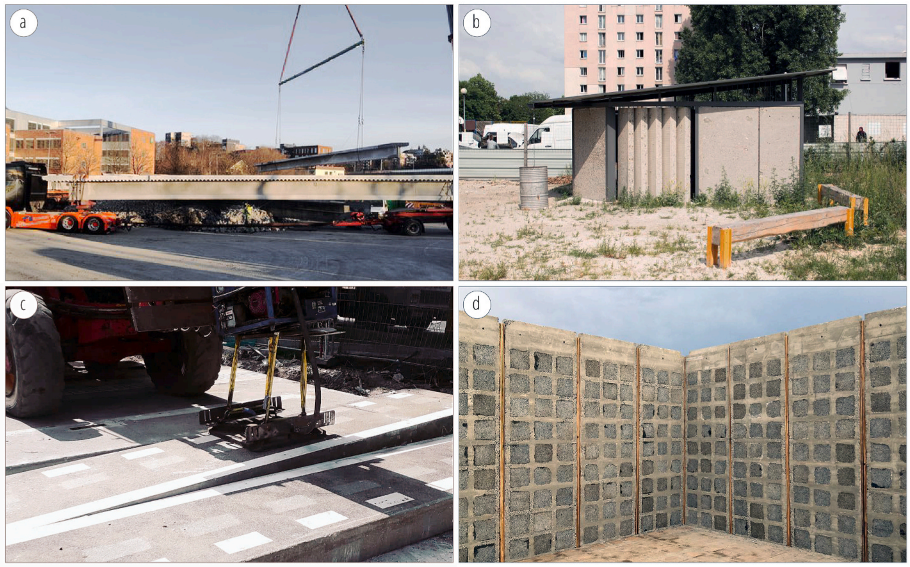


Fig. 14. Selection of case studies reusing precast elements: equivalent reuse of a bridge beam (C71), 2021 (a); reuse of pieces sawn from precast panels for new walls (C59), 2016 (b); reuse of platform tiles as pavement (C72), 2021 (c); and upcycling of garden tiles as self-standing walls (C61), 2018 (d). Image credits/sources: (a) Implenia (Implenia, 2021); (b) Clément Guillaume/Bellastock; (c) ale_archifre (2020); (d) EPFL/EAST (EAST/EPFL, 2019).

4.8. New applications reusing cast-in-place concrete pieces (trend G)

This last trend refers to the emergence since 2017 of new design solutions tackling the specificities of cast-in-place concrete reuse. As climate-change risks are rising and reuse in general is being more widely recognized as an efficient strategy towards a more sustainable construction industry, concrete reuse is gaining interest from governmental agencies and stakeholders beyond areas where prefabrication has been for long the predominant construction method. Consequently, since the late 2010s, twelve case studies – five built projects, one ongoing project and six Master theses – address the reuse of concrete elements extracted from cast-in-place obsolete structures. Indeed, although prefabrication has been extensively used for decades in some countries, many buildings concerned by demolition are partially or entirely made of cast-in-place concrete.

Cast-in-place concrete differs from precast concrete by its monolithic nature, the absence of explicit connection areas, and a highly customized production. Consequently, cast-in-place concrete may therefore seem more complex to reuse for some applications. However, C20, described in Section 4.4, already demonstrated in the 1990s the technical feasibility of cast-in-place PRECS in new housing projects. Except for the cut frames reused for an exhibition pavilion and houses (C60, C65), the collected case studies of this recent trend consider the reuse of cast-in-place concrete with a change of function: walls and foundation mats into prestressed blocks in a footbridge (C69, Fig. 15a) (Devènes et al., 2022b); building slabs into a parking slab (C68, Fig. 15b) (Küpfer

Fig. 15. Selection of case studies reusing cast-in-place concrete pieces: reuse of blocks in a prestressed footbridge (C69), 2021 (a); a parking pavement (C68), 2021 (b); and column supports (C77), 2022 (c). Reuse of large pieces in a pavilion and housing prototypes (C60, C65), 2017 and 2019 (d). Image credits/sources: (a) EPFL/SXL; (b) EPFL/Küpfer; (c) baubüro in situ; (d) SUPERLOCAL (Superlocal, n.d.).

et al., 2022); building elements into weight foundation blocks (C76) (Petersen, 2022). These three examples take advantage of the high compressive strength of concrete but do not use the tensile strength provided by the existing reinforcing bars, therefore illustrating a *downcycling* reuse.

One example that partly reuses both the compressive strength of concrete and the tensile strength of the reinforcement bars is C77, where new point foundations are built with salvaged concrete blocks that support bending moments, Fig. 15c. The engineer therefore recommended reusing blocks with a minimum amount of steel reinforcement, and a minimum concrete cover. Before installation, additional rebars are embedded in the blocks to link them together. In the end, a quarter of all the point foundations of the project were built with new concrete because of a lack of time to hunt the needed second-hand concrete pieces (Demierre, 2022).

A different approach than the reassembly of plane blocks is used to build a two-story exhibition pavilion (C60) and two housing prototypes (C65). In these case studies, large pieces of a monolithic structure are reused (Bremen Bouwadviseurs, 2018; Ritzen et al., 2019; Superlocal, 2020), Fig. 15d. These large box-like pieces are made of two walls and the lower and upper slabs. The slabs are cut further than the connection between the wall and the slab to minimize reassembly problems and make the most of the existing steel reinforcement. A downside of this approach is that the pre-existing layout of walls and slabs constrains the newly-built spaces.

Finally, several Master theses address certain issues of cast-in-place PRECS. For example, in 2019, Marshall (2019, 2020) develops a computational tool to arrange various-dimension sawn and broken concrete pieces (C64), which applies well to the non-serial nature of cast-in-place concrete. In 2019, Volkov (2019) designs connections to reuse typical load-bearing systems, including cast-in-place concrete structures (C63). As no clear assembly line exists in cast-in-place structures, Volkov suggests separating pieces where forces and bending moments are the lowest, in order to minimize technological value loss. In 2021, Demol (2021) sketches connection details for both precast and cast-in-place concrete salvaged pieces (C73). In 2022, Widmer (2022) develops an algorithm to allocate elements of donor slabs to a receiver building while minimizing the needs for new reinforcement (C75). Widmer also designs new wall-slab connections to reassemble reclaimed cast-in-place concrete elements into a new office building and confirms the environmental benefits of this PRECS practice.

4.9. Conclusions on the development trends

Overall, a rich diversity of feasible applications is identified and contrasts with the sparse number of case studies (77) collected. Considering the largest trends, PRECS practices have globally evolved from small applications reusing precast components (trend A, 1967–1998), to larger implementations (trend D, 1999–2010), to prototypes reusing cast-in-place pieces (trend G, 2017–2022). In addition to the aforementioned trends that cover most case studies (59), smaller trends contrast with this progression. The most contrasting trends are B and C, with the reuse of precast and cast-in-place concrete pieces in four large-scale projects, followed by the failed large-scale projects of trend E.

Finally, the diachronic analysis questions how the most recent trend of prototypes reusing cast-in-place pieces (trend G) will evolve in terms of scale and practice and whether the intensity of applications reusing cast-in-place and precast concrete will increase over the next decades. These forward-looking questions require a detailed understanding of the limiting and supporting forces surrounding PRECS, which are therefore explored in the following Section 5.

5. Synchronic analysis: supporting and limiting forces

5.1. Overview

A synchronic analysis of the collected data leads to the identification of supporting and limiting forces for the application of PRECS. They are collected according to five themes: techniques, environmental implications, economic implications, management and supply-chain, and design and sociocultural values. The following sections recapitulate all findings for each theme. The last section provides a cross-theme summary of supporting and limiting forces.

Limiting forces are differentiated between persistent constraints and transient barriers. Persistent constraints are defined as intrinsic unchangeable forces, for which no effective active leverage is thought to exist. Transient barriers are defined as current limiting forces for which it is assumed that one or several levers can remove them completely or partially. Transient or partly transient barriers are marked with a * symbol.

5.2. Techniques

5.2.1. Supporting forces

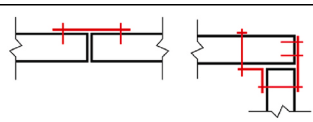
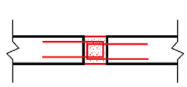
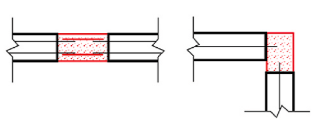
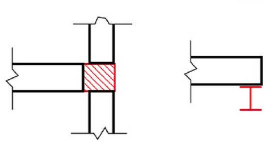
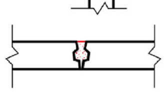
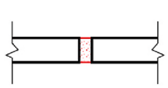
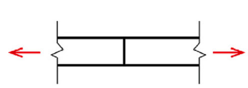
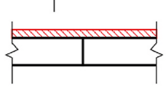
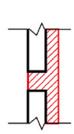
- *Availability of quality assessment tools.* Published records demonstrate that material properties of salvaged concrete and reinforcement steel can be verified using existing destructive and non-destructive techniques commonly used in the field of existing structures such as rebound hammer, ground-penetrating radar, load testing (Devènes et al., 2022b; Heyn et al., 2008b).
- *Availability of suitable concrete.* Case-study records confirm that salvaged concrete is principally in a very good state, which is well-aligned with the fact that the concrete has been, most times, extracted from relatively recent buildings and was well protected from deterioration while in the donor building.
- *Availability of deconstruction and construction tools and methods.* Collected PRECS projects are supplied and built combining existing deconstruction and construction tools and methods, often used in other construction contexts. For example, deconstructions are performed using diamond saws, hydro-blasting or local impact demolition, and lifting techniques used in prefabrication. When the original connections are lost, the reassembly typically relies on a combination of existing jointing – e.g. prestressing, embedding of new reinforcement bars – and reinforcement techniques – e.g. addition of carbon fiber lamellae, steel beams, or ultra-high performance concrete –, as documented, for example, in C29, C59, C69, or C77.
- *Compatibility with existing norms.* Existing structural-design norms are used to design PRECS structures (Devènes et al., 2022b; Küpfer et al., 2022).
- *Diversity of applications.* Several dozen design projects have already been successfully built with PRECS (see Appendix B) proving the technical feasibility. Built precast-PRECS projects include multi-story and row housing buildings, industrial and service buildings, agriculture and water management equipment, and bridges. Built cast-in-place-PRECS projects include a housing building, a footbridge, a parking pavement, foundations, an exhibition pavilion and house prototypes. PRECS benefits from inherent material properties of concrete, such as good load-bearing, fire-resistance and sound-proofing capacity, and, when well protected, durability.
- *Potential for innovation.* Technical innovation is a key driver in several case studies, including C29, C38, C54 or C69.

5.2.2. Limiting forces

- *Existence of unsuitable concrete.* Concrete pieces that are excessively damaged, degraded or contaminated by toxic substances are not suitable for reuse as structural elements (Devènes et al., 2022a; Gorgolewski, 2017).

- *Inexistence of industry standards or framework* (*). No approved standardized protocol is yet available for conducting material assessment for PRECS (Heyn et al., 2008b). Each engineering firm involved in PRECS case studies uses its own protocol to assess concrete and steel reinforcement quality as well as the condition state of the reclaimed elements (Devènes et al., 2022a). Consequently, liability aspects are addressed case-by-case, which may be discouraging.
- *Limited scope of deconstruction methods.* Technical constraints, such as the load bearable by lifting equipment, dimensions of openings on the extraction path, and maximum transportable dimensions, limit the maximum sizes of the pieces (Heyn et al., 2008a; Nagora, 2002). These constraint values vary according to the nature and situation of each project.
- *Limited scope of integration in receiver buildings.* As studied by Naber (2012), existing fire- and sound-proofing of the salvaged elements sometimes do not meet the normative requirements of new designs and must be improved.
- *Limited feedback on connection details* (*). Reusing concrete components typically implies designing and calculating tailored connection details. Indications on connection details are available for less than half of the case studies. These details could be organized into nine different categories, summarized in Table 2. The different techniques include dry connections, typically steel plates, or wet connections, using mortar or new concrete. These techniques are often combined to ensure the correct transmission of load effects. More research on connections is needed to reduce risks, inform on successful details, and lower technical unknowns.
- *Tendency for downcycling* (*). The number of precedents with *equivalent* or *upcycling* reuse of cast-in-place concrete is limited.
- *Limited feedback on material durability* (*). No study explicitly focuses on the durability of the PRECS projects. Despite the use over several decades of many of the structures and the fact that no static failure or damage of the cast-studies has been reported in the existing literature, studying the durability of the PRECS would be profitable for both researchers and potential future stakeholders.

Table 2
Connection types identified from the case-study documentation. Red lines and textures correspond to added reinforcement devices and concrete.

Connection-type description	Illustrative example	Featuring case studies
Steel plates or angles with bolts or anchor rods		C29; C31; C32; C34; C41; C54; C62; C63; C75
Post-installed rebars sealed with mortar or chemical adhesive		C54; C58; C59; C63; C67; C77
New rebars welded to existing ones, imbedded in mortar or concrete		C39; C47; C63;
Reinforced concrete or steel support beam		C34; C47; C50; C58; C59; C63; C75
Longitudinal shear key with reinforced mortar or concrete		C67
Mortar between pieces		C29; C31; C32; C34; C41; C62; C63; C68; C69; C77
Internal post-tensioning		C69
New structural topping with (reinforced) concrete		C75
Reinforced concrete matrix		C61

5.3. Environmental implications

5.3.1. Supporting forces

- *Precedence of global-warming-potential and environmental-impact reduction.* DEI reduction is a major driver of PRECS. The existing literature provides environmental analyses for 12 PRECS case studies. Fig. 16, built from the data listed in Appendix C, reviews the figures of existing analyses as found in the records. Despite the lack of homogeneity in the hypotheses and calculation methods, results all highly supportive as they all confirm – each for a given case study, different metric, and different analysis – the important reduction of environmental damages achieved using PRECS compared to conventional construction methods.
- *Precedence of reduction of waste and raw material consumption.* In most case studies, PRECS limits waste generation in large quantities due to the relatively large volumes and masses of concrete components reused in the new projects and diverted from landfilling or recycling. Additionally, PRECS reduces natural resource consumption as no new material needs to be produced besides the ones needed for the connections, retrofitting, and reinforcement (Asmus and Mettke, 2014; Küpfer et al., 2022; Naber, 2012).

5.3.2. Limiting forces

- *Risk of pollution shift.* At the project level, PRECS does not reduce environmental impacts, particularly global-warming potential, if the salvaged components are transported beyond a critical distance. This critical distance depends on the projects, but it is estimated at several hundred kilometers (Fischer et al., 2012; Glias, 2013; Roth and Eklund, 2000; Widmer, 2022), which, in the vast majority of PRECS projects, exceeds the radius that is necessary for the supply of components.
- *Limited availability of concrete waste.* At the construction-industry level, the total environmental benefits of PRECS cannot exceed a certain threshold that corresponds to the quantity of produced concrete waste (Marsh et al., 2022), which is the largest construction-waste stream. However, from a sustainable perspective, concrete waste should be reduced as much as possible by first extending on-site use, renovation and transformation strategies.
- *Unavailability of a robust comparative life-cycle assessment* (*). Existing environmental analyses of given case studies have yet been performed separately, and for a limited range of environmental indicators. A comparison of the impact reduction of multiple PRECS projects, for several indicators, would enhance knowledge on potential environmental benefits of PRECS. However, data availability might remain a difficult challenge to overcome, particularly for the oldest case studies.

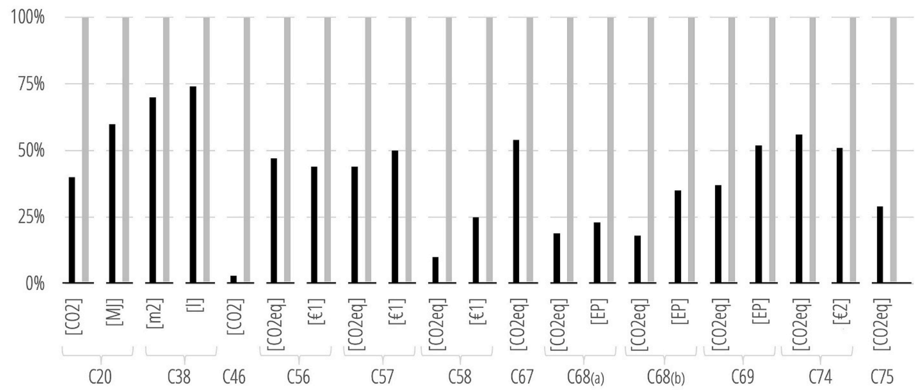


Fig. 16. Ratios of DEI between PRECS (black) and each of their corresponding conventional alternative (grey), as found in the literature. Results are expressed in CO_2 emissions [CO_2], energy use [MJ], land use [m^2]; oil [l]; global-warming potential [CO_2eq], shadow price [€$_1$], ecological load [EP], or environmental costs [€$_2$]. Full data set presented in Appendix C.

5.4. Economic implications

5.4.1. Supporting forces

- *Existence of profitable precedents.* Under certain circumstances, PRECS is economically advantageous. In Fig. 17, black bars smaller than adjacent grey ones indicate economic savings when compared to conventional alternatives, as identified in the case-study records. Savings are supported by reduced salvaged material costs and by limiting operations on the salvaged pieces (Küpfer et al., 2022). For example, in C2 and C3, a record reports that salvaged panels have cost one third of the price of new ones (Huuhka et al., 2019). In C30, saving on structural materials are claimed to be achieved by reducing operations on reclaimed pieces to only minor drilling (Gorgolewski, 2017). Demolition companies tend to donate the salvaged concrete pieces because they often represent waste for them, for which landfill taxes may apply (Küpfer et al., 2022; Widmer, 2022).
- *Expectation of positive impacts on labor.* Reusing materials, including PRECS, is consistent with a sustainable service-based economic transition, as it entails a new distribution of construction costs that favors labor over new material import (Addis, 2006; Bellastock, 2018; Küpfer et al., 2022) and fosters local employment in non-relocatable jobs (Chantereau, 2017).
- *Potential for new job creation.* Reusing materials, including PRECS, is an opportunity to create new types of jobs and business models, like material hunters, reuse-potential assessors or refurbishment experts, as new phases in the project process are needed (Ghyoot et al., 2018; Gorgolewski, 2017).
- *Expectation of positive impacts on cost control.* Reuse, in general, allows the construction project to be supplied with locally available materials via non-globalized markets. Consequently, project costs are less dependent on the fluctuations of new-construction-material prices on the world markets.
- *Expectation of future, more beneficial economic context.* Economic attractiveness of salvaged material will increase if landfill tax, energy or raw-material price increases (Dunant et al., 2018), if new climate-emergency-driven policies economically favoring grey-energy reduction are implemented, or if labor taxation decreases (Ghyoot et al., 2018).

5.4.2. Limiting forces

- *Existence of non-profitable precedents* (*). Under certain circumstances, PRECS is more expensive than conventional construction techniques. Black bars higher than adjacent grey ones on Fig. 17 indicate extra economic costs when compared to conventional alternatives, identified in the case-study records. Extra costs are typically due to the labor-demanding nature of the strategy and/or to the pioneering dimensions of some case studies that lead to time-consuming and non-optimized processes (Bellastock, 2018; Huuhka et al., 2019; Küpfer et al., 2022).
- *Necessity for new costly expenses* (*). Deconstruction and reconditioning operations today are costly positions. Küpfer et al. (2022) conclude that sawing and drilling operations should be kept minimum to allow the concrete reuse to be economically competitive. Heyn et al. (2008b) similarly stress the importance of limiting additional work on the concrete parts to lower costs. Finally, Bremen

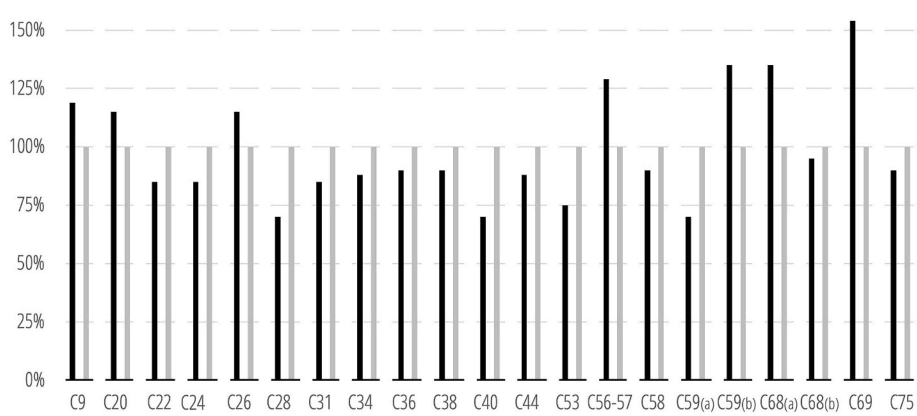


Fig. 17. Ratios of construction cost between PRECS (black) and each of their conventional alternative (grey), as found in the literature. In the case of a value range, the least favorable value to PRECS is presented here. Full data set available in Appendix D.

Bouwadviseurs (2018) and Bellastock (2021) suggest that the various implied processes – e.g. sawing, lifting and reconnection – need to be optimized to limit costs.
- *Limited availability of financial records* (*). The small size of the reference set prevents planners from comparing and validating their cost estimations with fully comparable built references.

5.5. Management and supply-chain

5.5.1. Supporting forces

- *Possibility of increased control over procurement planning.* Studied PRECS projects are supplied via a local or regional supply chain independent of globalized markets and their delays.
- *Possibility of decreased construction time.* As underlined by Gorgolewski (2017), reused concrete pieces, like precast concrete, do not require curing time, which speeds up the construction process compared to cast-in-place concrete.

5.5.2. Limiting forces

- *Unsuitability of conventional project management* (*). Compared to conventional practice with new or recycled materials, PRECS, like the reuse of other materials, modifies the project-management process. PRECS typically requires additional project stages, such as existing-concrete-piece hunting and assessing, and generally complicates project management, as recognized, among others, by (Devènes et al., 2022b; Heyn et al., 2008b).
- *Inexistence of a reseller network* (*). No network of reused-concrete-piece resellers currently exists. Therefore, PRECS supply chain entails significant synchronization efforts between donor site and receiver project, and collaboration between involved actors from early project phases, as recognized, among others, by (Al-Faesly and Noël, 2022; Bremen Bouwadviseurs, 2018; Glias, 2013). Indeed, PRECS projects depend on donor-site deconstruction planning, potential delays, unexpected issues, and planned temporary storage spaces.
- *Prevalence of demolition practices* (*). Demolition nowadays largely prevails over careful deconstruction. Because careful deconstruction is inherently more time-consuming, it is only applied on sites where nuisance or project constraints require it – e.g. dense urban context, transformation – unless it is envisioned as part of a larger reuse strategy. Thus, despite the large amount of demolished concrete (Böhmer et al., 2008), the flow of carefully extracted concrete pieces is limited and additional efforts or negotiations with potential project donors are sometimes necessary to supply some PRECS projects (Demierre, 2022; Devènes et al., 2022b).
- *Necessity for new liability contracts* (*). Reusing concrete – like reusing any structural component, as described by Gorgolewski (2008) – questions the classic construction-project liability scheme. Indeed, with new or recycled materials, engineering firms are responsible of all structural verifications and subsequent planning through drawings and material bills, while construction companies are responsible for the quality of materials put in place and the geometrical tolerances of components. But in the case of PRECS, material quality and geometrical tolerances both depend on the assessment made by the engineering firm, the quality of work by the deconstruction company and that of the construction company. Therefore, the classic scheme must be adapted on case-by-case basis. This question is to be further discussed between standardization bodies, professional associations, and insurance companies.

5.6. Design & socio-cultural values

5.6.1. Supporting forces

- *Possibility of heritage valorization.* While reporting on C54, Fisher et al. highlight the socio-cultural implications of PRECS (Fischer et al., 2012). Designing from pieces with pre-existing features adds singularity to projects, prolongs the history of the component, and roots the project in its territory, offering a possibility to preserve the heritage value of the components and valorize the technical know-how embedded in the reclaimed components.
- *Possibility of new craft valorization.* Chantereau (2017) recognizes the technical-cultural value of the human work behind the reuse of concrete and compares it with that of a stone mason, thus linking it to a form of craftsmanship.
- *Possibility of aesthetic independence.* As with the reuse of other load-bearing elements, the appearance of second-hand concrete components can be concealed behind other building layers. This design approach has been largely used before 2010 in the facades of many case studies of trends B and D, where reused components are invisible.
- *Possibility of new aesthetics.* Occasionally from 2004 and frequently since 2012, reused concrete pieces are left visible to the visitor, manifesting the reuse, its visual particularities and aesthetic opportunities. Aesthetic opportunities include, among other, the terrazzo-like cut slices of concrete, like in C59 or C69, or the mosaic-like combination of different concrete surfaces, like in C68.

5.6.2. Limiting forces

- *Risk of higher tolerances* (*). Deconstruction and preparation operations on salvaged concrete components are today performed with lower precision than in prefabrication plants (Devènes et al., 2022b). Therefore, PRECS details are often designed to tolerate geometric and mechanical variabilities.
- *Tendency to restrict design freedom* (*). As operations on concrete components are – in the current economic context – costly, design projects are sometimes adapted or constrained to minimize operations (Küpfer et al., 2022).
- *Necessity to consider stock availability.* PRECS design is a stock-constrained design task. Three stock-constrained design situations are identified from the case-study corpus:
  - (A) Components identified for reuse are reclaimed before the project design starts. Thus, the design process cannot influence the disassembly pattern (or the parting lines) between the reclaimed components and is constrained by their specificities (C22, C51, C64).
  - (B) A donor structure is already identified when the project design starts, but pieces are not disconnected yet. The design process thus, to some extent, influences and adjusts the disassembly pattern by iterating with the new design project (C60, C65).
  - (C) The project design starts before the donor structure or reclaimed pieces are identified. Good knowledge of the stock is required to ensure that the needed pieces are discarded on a regular basis in the given region. In this case, structural systems and details have to be pre-designed to accommodate pieces with not exact and unique dimensions but with minimum and maximum dimensions (C68, C69, C77). When later hunting for the pieces, there are two possible options: either the project design influences the identified donor disassembly pattern (as in situation B) or does not (as in situation A).
- *Occasional necessity to control the disassembly pattern.* Defining the disassembly pattern is more complex for cast-in-place-concrete donors than for precast-concrete ones. For the latter, the disassembly pattern between pieces typically follows the original connections between precast elements. Conversely, for cast-in-place structures,

their monolithic nature prevents trivial disassembly pattern. As Volkov (2019) and Widmer (2022) suggest, an iterative design approach is needed to draw coherent parting lines and, ideally, limit *downcycling.*

- *Necessity to adapt designs to reuse specificities.* Two attitudes toward stock-constrained design have been identified and studied by Naber (2012). In one case, the project is designed without being strongly adapted to reusable pieces, which typically reduces the rate of reused pieces in the final project. In a second case, the project is adapted to reusable pieces up to the desired amount, which modifies the design process and its result more strongly.
- *Necessity to integrate visual defects.* Designing with reclaimed components involves dealing with existing traces, paint, plaster, or other overlays. In the case of concrete, these marks of the past can be hidden behind other constructive layers. But if the architectural concept includes exposed concrete, the designer is then constrained to perform an appearance assessment of the pieces or work with possibly less controlled aesthetics.
- *Perception of risks* (*). In a conservative industry where the notion of liability is paramount, the exploratory dimension of concrete reuse remains a cultural constraint (Bellastock, 2018). Moreover, contrary to steel, concrete has a heterogeneous nature which adds to the concerns regarding the technical value of reclaimed elements. As for many projects reusing structural elements and despite the precedents identified in this study, risks are often still viewed as being too high, both by designing teams and construction companies (Gorgolewski, 2017).

5.7. Conclusions on supporting and limiting forces

Overall, the synchronic analysis shows that existing supporting forces provide a solid foundation for future developments of PRECS. Indeed, the availability of tools, suitable discarded concrete, and cost-effective and environmentally-beneficial precedents, in addition to the valorization of heritage and new crafts, are strong supports to PRECS adoption. Certain strengths, such as reduced environmental impacts and labor-oriented methods, are expected to be emphasized in a future with a more sustainable and circular construction context.

The synchronic analysis shows that persistent constraints to a wider application of PRECS are mostly due to the particularities of existing concrete structures and mainly relate to project-management, design and technical aspects. They include: the maximum dimensions of reusable concrete pieces as given by the features of existing structures; their occasional toxicity or degradation; the eventual need for fire- or sound-proofing improvement; and the stock-constrained nature of the design task. The implications of the latter can, however, be partially minimized by tailored design tools and the combination with new or recycled materials.

Besides, the analysis supports that transitional barriers are often related to perceived risks due to gaps in knowledge about technical and liability aspects, and to some extent to the structure of the construction industry. Overcoming transient barriers is discussed further in Section 6.2.

6. Discussion

6.1. Study and result limitations

This study and its conclusions are bound to a number of limitations. First, this study is only building on records that have been published and that are publicly available. Because many other unpublished applications of PRECS may exist, the case-study corpus is most probably not exhaustive. Additionally, the record search has been performed on a given set of databases, first only in English and then extended to local languages of identified research projects and case studies. Case studies have been identified in Europe and the USA only, and cases in other territories might be missing. The methodology could be further improved by extending the search query to other record databases and search languages.

Second, data quantity and quality vary across case studies. Implications of a given case study on the design process, results and sustainability area are often only partly documented and detailed. A collection of new original data on the case studies could be pursued, but is challenged by documentation availability and archival issues.

Third, the study analyzes the PRECS strategy in various countries of Europe and North America. Although these economic contexts and built environments may have similarities, construction standards, risk-management culture, economic specificities, and environmental impacts vary from one country to another. Future work could extend the analysis with in-depth country-specific investigations.

Finally, the detection of trends and periods stem from an iterative comparative process. The additional identification of past or recent case studies might suggest adding a trend or discussing the limit of an existing one. Additionally, new knowledge, applications and modified socio-economic contexts will doubtlessly alter the identified supporting and limiting forces of PRECS.

6.2. Leveraging actions for a wider application

Sections 5.2 to 5.6 identified transient barriers against a wider application of reuse in practice. Leveraging actions typically address several barriers simultaneously; they can be direct or indirect and implementable at different time horizons.

First, research can play a role in reducing the unknowns and leveraging knowledge-gap limitations regarding for example, connection details, structural durability, additional design options, and existing concrete stock and availability. Then, collaborations of research entities with normalization bodies and practitioners will be imperative to elaborate technical guidance, including standardized material-assessment protocol and reconstruction details.

On a project level, the implementation of the reuse strategy globally depends on the perceived risks from clients and design teams. Risk perception modification is a slow and intricate process. The development of technical guidance is a necessary step in this direction. The documentation and analysis of precedents must also be pursued to better inform stakeholders on real risks and benefits and vanish this barrier.

Practical barriers due to relatively low demand and inexistent supply chain are market-related and depend on value-chain actors. National politics, regional initiatives on the circular economy, and new economic models for matching donor and receiver buildings are influential tools to lever these synchronization issues. The existing situation could rapidly evolve with society efforts to develop a circular economy and achieve sustainability goals. For example, if new laws significantly increase landfill or CO_2 taxes, attractiveness of reuse and other circular activities is expected to directly increase.

Besides these active and specific levers, one should not minimize the role of indirect passive factors on the reuse of components induced by the global economic context. Costs of energy and imported materials is subject to rapid evolutions fastened by crises, and their precipitation might, too, suddenly spark new interest in reuse activities.

6.3. Future research priorities

To better define PRECS potential as a sustainable construction strategy and further implement it, three topics are identified as future research priorities: knowledge on past construction techniques; larger set of proven design solutions, including reconnection details; decompartmentalization of expertise.

Knowledge on the existing built stock in concrete and on past construction techniques would help better predict the quantity and quality of discarded concrete pieces. Understanding how concrete buildings have been constructed in the past 50 years, what they are made of, and how to deconstruct them allow designers to start first sketches of projects more quickly, based on availability predictions. It would also decrease the dependency between design processes and uncertainties on material availability, hence reducing the related extra costs.

More research on design solutions is needed to expand the set of proven methods and help better define the field of architectural and engineering possibilities of PRECS. Emphasis should be placed on the development and analysis of past and new re-connection details. Moreover, research on new structural re-connection systems for *equivalent* and *upcycling* reuse of cast-in-place concrete pieces is notably lacking. Indeed, cast-in-place-PRECS applications today are mostly limited to *downcycling* reuse, and the potential of cast-in-place, reinforced PRECS in more demanding applications remains unproven.

A decompartmentalization of expertise is needed to achieve those two first goals and the many others needed before large-scale implementation of PRECS. Most knowledge and techniques already exist but are specific to the fields of architectural design, structural design, maintenance, construction technology and history, waste management, deconstruction and structural strengthening. Cross-disciplinary development would speed up innovation on PRECS and, like circular reuse in general, would call for dedicated research, education and training.

6.4. Relevance

In the alarming context of environmental, social, and economic crises, sustainable strategies must be implemented to reduce the damaging impacts of the construction industry on the environment and the living world. This work actively contributes to the multidisciplinary knowledge necessary to discuss the role of PRECS among other sustainable construction strategies. While decarbonization plans rarely consider PRECS, the analysis clearly attests to the significant greenhouse gas savings achieved with PRECS in several projects and the existing and potential socio-economic benefits of recirculating and reusing urban-mined concrete. On the other side, the study highlights several project-management challenges, project-design implications, and the limited set of financial references. Overall, the study encourages a needed debate on the role of PRECS in the scientific literature, and in the concrete-industry and construction-sector plans for environmental impact reductions.

Besides, the database provides a large set of built references for designers, funding bodies and the construction industry. Not only its analysis contributes to new knowledge in construction history, it provides researchers and stakeholders an ample state of knowledge on the drivers, limitations and levers of PRECS, both at a project and industry scale, that will help them taking informed decisions for future actions.

7. Conclusions

This paper critically reviews the state of practice and knowledge on the Piecewise Reuse of Existing Concrete in new Structural assemblies (PRECS). Through a robust literature and case-study collection, the study builds an original database of 77 PRECS case studies in Europe and the USA, of that 54 are built projects. The case-study and record collection analyses lead to the following conclusions:

- The practice of PRECS has a long history. It has evolved through time, with a pioneering period starting in 1967 until the end of the 1990s, mostly in Northern Europe. Since 2011, the interest of concrete reuse has widened both in terms of type of reused components but also in terms of territories. Lately, the reuse of components extracted from cast-in-place concrete structures has gained interest.
- A large diversity of built projects has been identified, but the full potential scope of PRECS application remains unproven. Notably, a lack of applications involving equivalent or upcycling reuse of components extracted from cast-in-place concrete structures has been recognized.
- The availability of tools, suitable discarded concrete pieces, and cost-effective and environmentally-beneficial precedents, in addition to the valorization of heritage and new crafts, are strong supports to PRECS wider adoption.
- Limiting forces to a broader implementation of PRECS include technical fears, project-management risks and synchronization issues. However, many limitations are perceived as liftable transitional barriers and expected to vanish providing an appropriate development.

Envisioning the reuse of urban-mined concrete pieces as a needed pathway for greater sustainability and circularity in the construction industry, the authors call for better knowledge on the built stock and past construction techniques, an extension of the set of proven design solutions and connection details, and a decompartmentalization of areas of expertise.

Today, most literature listing the available pathways for cleaner construction do not include the reuse of concrete pieces in new buildings as a strategy to consider. With this paper, the authors support that sufficient literature and precedents exist to engage a shift of mindset among researchers, policymakers, and practitioners.

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CRediT authorship contribution statement

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

Declaration of competing interest

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

Data availability

Data will be made available on request.

Appendix A. Collected records

Appendix A presents and classifies the 90 collected records per type and publication decade. In parenthesis, number of records per line or column, respectively.

	1980–1989 (2)	1990–1999 (3)	2000–2009 (26)	2010–2019 (33)	2020–2022 (26)
Journal articles (8)			(Gorgolewski, 2008; Künzel, 2005)	(Huuhka et al., 2015, 2019; Salama, 2017)	(Devènes et al., 2022b; Marsh et al., 2022; Marshall et al., 2020)
Conference papers and presentations (18)			(Avak and Schwuchow, 2007; Eklund et al., 2003; Hagan and Kontukoski, 2009; Kristinsson et al., 2001; Mettke, 2008; Roth and Eklund, 2000; te Dorsthorst et al., 2000, 2001; te Dorsthorst and Kowalczyk, 2001)	(Hopkinson et al., 2018; Kozminska, 2019; Mettke, 2017; Orchowska, 2017; Ritzen et al., 2019)	(Al-Faesly and Noël, 2022; Küpfer et al., 2022; Vergoossen et al., 2021, 2022)
Books and book chapters (10)	Mühlestein (1987)	(Coenen et al., 1990; Gieselmann, 1991; Mettke, 1995)	(Addis, 2006; Asam, 2007b)	(De Graaf, 2018; Gorgolewski, 2017; Huber, 2013; Vogdt et al., 2016)	
Doctoral and post-doctoral theses (3)			(Nagora, 2002; Roth, 2005)	Mettke (2010)	
Master theses (13)				(Dolkemade, 2018; Glias, 2013; Marshall, 2019; Naber, 2012; Volkov, 2019)	(Demol, 2021; Devènes, 2021; Jabeen, 2020; Kamp, 2021; Strauss, 2021a, 2021b; van den Brink, 2020; Widmer, 2022)
Reports/Factsheets (18)			(Asam, 2005, 2007a; Asam et al., 2005; Heyn et al., 2008a, 2008b; Huber, 2008)	(Asmus and Mettke, 2014; Bellastock, 2018; Bremen Bouwadviseurs, 2018; Dechantsreiter, 2015; Fischer et al., 2012; Hradil et al., 2014; Janorschke et al., 2010; Nationale Stadtentwicklungspolitik, 2017; Rundschau, 2016)	(Bellastock, 2021; Devènes et al., 2022a)
Magazine/press articles, interviews, webpages, videos (20)	Irion and Sieverts (1984)		(ArchDaily, 2009; IAB Weimar, 2005; Kil, 2007; Polony, 2008; WBK21, 2005)	(Chantereau, 2017; Hagan, 2013; Meyer, 2018; Nationale Stadtentwicklungspolitik, 2017; SsD, 2014; Superlocal, 2018)	(Arc2 architecten, 2021; bauburoinsitu, 2022; Borges, 2022; Comment, 2021; Demierre, 2022; Hof van Cartesius, 2021; Implenia, 2021; Petersen, 2022; Superlocal, 2020)

Appendix B. case-study list

Appendix B lists the identified case studies – i.e. design solutions involving the Piecewise Reuse of Existing Concrete in new Structural assemblies (PRECS) – and key information on them. The chronological list is not exhaustive. Data based mainly on assumptions are in italic. List of abbreviations: PC: precast; CIP: cast-in-place; Unk.: Unknown; Abort.: aborted; Study: study work; CP: component(s); SF: the same function.

Case-study code	Top line: PRECS case-study description Bottom line: (Receiver-) project name	Main concrete type	Receiver-project location (Country)	Approx. distance from donor building in [km]	PRECS case-study date (start)	Component age at receiver construction start (approx.)	Design-solution status	Reference
C1	Reuse of floor slabs from a 6-story reinforced-concrete skeleton building for floor stabilization in a new plant							Mettke (1995)
	Leipzig plant	*PC*	*Leipzig (D)*		1967	37	Built	
C2	Reuse of panels of the Ingebäck PC system from a lowered mass-housing building for facade and slabs in a new 7-story housing building							(Fischer et al., 2012; Gieselmann, 1991; Huuhka et al., 2019; Irion and Sieverts, 1984; Künzel, 2005; Mühlestein, 1987)
	Gothenburg 7-story building	PC	Gothenburg (S)	circa. 16	1984	16	Built	
C3	Reuse of panels of the Ingebäck PC system from a lowered mass-housing building for *facade and slabs* in new low-rise houses							(Fischer et al., 2012; Gieselmann, 1991; Huuhka et al., 2019; Irion and Sieverts, 1984; Mühlestein, 1987; Nagora, 2002)
	Gothenburg row houses	PC	Lerum/ Kungälv/ Backatorp (S)	circa. 19	1984	16	Built	
C4	Reuse of wall panels from a gym hall to reinforce the ground of a construction-material storage facility							Mettke (1995)
	Cottbus storage facility	PC	Cottbus (D)	10	1985	7	Built	
C5	Reuse of plinth wall panels from a gym hall for SF in the extension of the same building							Mettke (1995)
	Cottbus gym hall extension	PC	Cottbus (D)	0	1985	7	Built	
C6	Reuse of solid wall frames, purlins, and "gas-beton" CP. From two halls for SF in the relocated halls							Mettke (1995)
	Meuro relocated ind. Halls	PC	Meuro (D)	2	1986	14	Built	
C7	Reuse of purlins, V-columns, sleeve foundations, gable shear CP. From two shelters for SF in a new shelter							Mettke (1995)
	Cottbus shelter	PC	Cottbus (D)	0	1986	16	Built	

(*continued on next page*)

(*continued*)

Case-study code	Top line: PRECS case-study description Bottom line: (Receiver-) project name	Main concrete type	Receiver-project location (Country)	Approx. distance from donor building in [km]	PRECS case-study date (start)	Component age at receiver construction start (approx.)	Design-solution status	Reference
C8	Reuse of roof cassette panels from two industrial buildings for SF in a guardian house							Mettke (1995)
	Spremberg guardian house	PC	Spremberg (D)	3	1986	18	Built	
C9	Reuse of 900 slab, facade, balcony, and roof panels for SF in new 3- and 4- story housing blocks							(Coenen et al., 1990; Fischer et al., 2012; Glias, 2013; Huuhka et al., 2019; Kristinsson et al., 2001; Naber, 2012; Salama, 2017; te Dorsthorst et al., 2000)
	Middelburg housing blocks	PC	Middelburg (NL)	*< 5*	1986	14	Built	
C10	Reuse of gable wall panels from a factory as walls in the same building							Mettke (1995)
	Pirna factory	PC	Pirna (D)	0	1988	15	Built	
C11	Reuse of columns as trip foundations in the extension of the same building							Mettke (1995)
	Spremberg Hall extension	PC	Spremberg (D)	0	1988	18	Built	
C12	Reuse of gable walls from a plant as wall panels in the same building							Mettke (1995)
	Weisswasser heating plant	PC	Weisswasser (D)	0	1988		Built	
C13	Reuse of 100% of solid wall panels, purlins, "gas-beton" CP, and 60% of plinth wall panels for SF in a relocated hall							Mettke (1995)
	Barwälde storage hall	PC	Bärwalde (D)	6	1988	10	Built	
C14	Reuse of roof cassette panels, trusses, and wall CP for *SF* in a relocated building.							Mettke (1995)
	Bärwalde industrial building	PC	Bärwalde (D)	6	1989	14	Built	
C15	Reuse of 100% of trusses, above-ground outdoor wall panels, and 50% of roof cassette panels for *SF* in a relocated workshop							Mettke (1995)
	Bärwalde workshop 1	PC	Bärwalde (D)	4	1989	11	Unk.	
C16	Reuse of roof cassette panels from a stable for *SF* but higher loads in new garages							Mettke (1995)
	Kahren garage	PC	Cottbus (D)	0	1990	20	Built	
C17	Reuse of columns and roof cassette and wall panels for SF in a relocated hall							Mettke (1995)
	Altenberg hall	PC	Altbenberg (D)	0,5	1990	14	Unk.	
C18	Reuse of roof cassette panels, trusses, and columns for SF in a relocated workshop							Mettke (1995)
	Bärwalde workshop 2	PC	Bärwalde (D)	6	1990	11	Built	
C19	Reuse of 100% of CP for a building relocation							Mettke (1995)
	Barwälde Polytechnique Center	PC	Bärwalde (D)	28	*1991*	*15*	Unk.	
C20	Reuse of 1850 t of CIP concrete wall elements, floor beams and foundations from two large buildings reused into a 22-apartment building							(Addis, 2006; Eklund et al., 2003; Roth, 2005; Roth and Eklund, 2000)
	Udden student apartments	CIP	Linköping (S)	64	1997	35–40	Built	
C21	Reuse of trusses from an industrial building for SF in a new industrial building							(Fischer et al., 2012; Mettke, 2017)
	Lauchhammer industrial hall	PC	Lauchhammer (D)	20	1998	27	Built	
C22	Reuse of 16 wall panels of the WBS70 PC system from mass housing in a new house							(Dechantsreiter et al., 2015; Fischer et al., 2012; Heyn et al., 2008b; Mettke, 2008, 2010; Nagora, 2002)
	Eggesin house	PC	Eggesin (D)	2	1999	24	Built	
C23	Reuse of 26 wall and 50 slab panels of the P2 PC system from mass housing in a new twin-house							(Dechantsreiter et al., 2015; Fischer et al., 2012; Heyn et al., 2008b; Mettke, 2008, 2010)
	Bröthen twin-house	PC	Hoyerswerda (D)	6	2001	32	Built	
C24	Reuse of 274 panels of the P2 PC system from mass housing in five new *3-story* houses							(Dechantsreiter et al., 2015; Fischer et al., 2012; Heyn et al., 2008b; Künzel, 2005; Mettke, 2008, 2010; Nationale Stadtentwicklungspolitik, 2017)
	Five Cottbus urban houses	PC	Cottbus (D)	0	2001	25	Built	
C25	Aborted project to reuse panels of the Elementum PC system from mass housing in new *housing*							(Glias, 2013; Kristinsson et al., 2001; Naber, 2012; te Dorsthorst et al., 2001; te Dorsthorst and Kowalczyk, 2001)
	Maasluis	PC	Maasluis (NL)	0	*2001*	*30*	Abor.	
C26	Reuse of 400 CP (partition walls, external walls, beams, staircases) from lowered buildings in 54 new flats, while 500 were planned							(Addis, 2006; Eklund et al., 2003; Glias, 2013; Salama, 2017)
	Nya Udden apartments	PC	Linköping (S)	40	2002	30	Built	
C27	Reuse of 6 external-wall panels, of which one is resized, and 6 slab panels of the WBR80-E PC system from mass housing in a new car garage							(Dechantsreiter et al., 2015; Mettke, 2010)
	Mellingen car garage	PC	Mellingen (D)	125	2004		Built	
C28	Reuse of 8 wall panels of the WBR80-E PC system from mass housing in a mourning room, reinforced with timber							(Dechantsreiter et al., 2015; Fischer et al., 2012; IAB Weimar, 2005; Janorschke et al., 2010; Mettke, 2010)
	Mellingen mourning room	PC	Mellingen (D)	125	2004		Built	

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Case-study code	Top line: PRECS case-study description Bottom line: (Receiver-) project name	Main concrete type	Receiver-project location (Country)	Approx. distance from donor building in [km]	PRECS case-study date (start)	Component age at receiver construction start (approx.)	Design-solution status	Reference
C29	Reuse of panels from the WBS70 PC system from mass housing in a design-for-disassembly exhibition prototype, with cut panels reinforced with carbon lamellae							(Asam, 2005, 2007a, 2007b; Fischer et al., 2012; Kozminska, 2019)
	Plattenpalast prototype	PC	Berlin (D)	18	2004	20	Built	
C30	Aborted project to reuse “Inverset” steel-concrete bridge-deck elements from a highway ramp in a multi-unit building							(Gorgolewski, 2008; SsD, 2014)
	Big Dig Building	PC	Boston (USA)		2004	55	Abor.	
C31	Reuse of 22 wall and 27 slab panels (118 m^3), of which some are resized, of the WBS70 PC system from mass housing in a flat-roof house							(Asam, 2007a, 2007b; Asam et al., 2005; Dechantsreiter et al., 2015; Fischer et al., 2012; Heyn et al., 2008b; Huuhka et al., 2019; Salama, 2017)
	Mehrow 1st pilot house	PC	Mehrow (D)	8 or 17	2005	21	Built	
C32	Reuse of 200 pieces (245m^3) sawm from 60 floor and 50 interior-wall panels of the WBS70 PC system from mass housing in a pitched-roof house, with a two-story atrium and where only the staircase is made of new concrete							(Asam, 2007a, 2007b; Asam et al., 2005; Fischer et al., 2012; Huuhka et al., 2019)
	Berlin-Schildow 2nd pilot house	PC	Schildow (D)	33	2005	18	Built	
C33	Reuse of 21 internal-wall and 16 prestressed-slab panels of the WBR80-E PC system from mass housing as transverse walls and roof panels in car shelters, using new reinforcement bars and circular anchors for reinforcement							(Dechantsreiter et al., 2015; Heyn et al., 2008b; Janorschke et al., 2010; Mettke, 2008, 2010)
	Waltershausen Car shelters	PC	Waltershausen (D)	0	2006		Built	
C34	Reuse of 2 external-wall, 7 internal-wall, 6 slab, and 3 roof panels, of WBS70 PC system from mass housing, in a new house where some all panels are resized, and reused panels are combined with bricks and mortar							(Heyn et al., 2008b; Mettke, 2010; WBK21, 2005)
	Berlin-Werneuchen house (Haus Pieper)	PC	Werneuchen (D)	26	2006	19	Built	
C35	Reuse of panels (91m^3) of WBS70 PC system from mass housing in a new house, where slabs are also reused as walls for higher spaces.							(Asam, 2007a; Fischer et al., 2012; Huuhka et al., 2019)
	Berlin-Karow 3rd pilot house	PC	Karow (D)	23	2006	22	Built	
C36	Reuse of 6 external wall, 13 internal-wall, and 26 slab panels of the WBR Erfurt 82 PC system from mass housing, in a new house							(Dechantsreiter et al., 2015; Fischer et al., 2012; Heyn et al., 2008b; Kil, 2007; Mettke, 2008, 2010)
	Leinefelde house	PC	Leinefelde (D)	0,5	2006		Built	
C37	Reuse of 17 wall and 14 slab panels, and 1 staircase from the IW73 PC system from mass housing in a new house							(Dechantsreiter et al., 2015; Fischer et al., 2012; Heyn et al., 2008b; Mettke, 2010, 2017)
	Plauen house	PC	Plauen (D)	2	2006		Built	
C38	Research project on the reuse of slab panels from the WBS70 PC system from mass housing as dike elements, where panels were cut into halves to test more joints							(Dechantsreiter et al., 2015; Heyn et al., 2008b)
	Dike prototypes in Welzow Süd	PC	Welzow Süd (D)	90	2006	20	Built	
C39	Reuse of 5 external-wall and 8 slab panels from the P2 PC system from mass housing in a garage, with 4 slabs reused as groundfloor pavement							(Dechantsreiter et al., 2015; Heyn et al., 2008b; Mettke, 2010)
	Weisswasser garage	PC	Weisswasser (D)	*<10*	2007		Built	
C40	Reuse of 28 wall and 23 slab panels, and 7 staircases of the WBS70 PC system from mass housing in a multi-family housing							(Dechantsreiter et al., 2015; Fischer et al., 2012; Heyn et al., 2008b; Mettke, 2010)
	Mühlhausen 2-story multi-housing building	PC	Mühlhausen (D)	28	2007		Built	
C41	Reuse of internal-wall and slab panels from the WBS70 PC system from mass housing in one- and two- story houses							(De Graaf, 2018; Dechantsreiter et al., 2015; Fischer et al., 2012; Heyn et al., 2008b; Mettke, 2008, 2010)
	Brielow single-family house development	PC	Brielow (D)	100	2007	23	Built	
C42	Reuse of 145 floor, 19 external-wall, 14 internal-wall, and 11 basement-wall panels of the IW73/6 PC system from mass housing in a new sport-association house							(Fischer et al., 2012; Heyn et al., 2008b; Mettke, 2010)
	Plauen association house	PC	Plauen (D)	7	2007		Built	
C43	Reuse of 279 CP (exterior and interior walls, interior wall frames, slab elements, plinth panels, and staircases) from a Dresden-type school, and of 159 panels of the WBS70 PC system from another building in a new sport-association house, using a layer of bricks to level the walls and overlapping facade CP							(Dechantsreiter et al., 2015; Heyn et al., 2008b; Mettke, 2008, 2010; Polony, 2008)
	Gröditz association house	PC	Gröditz (D)	2,5	2007		Built	
C44	Reuse of external-wall, internal-wall and slab panels of the WBS70 PC system from mass housing in new two-family houses without resizing the components							Heyn et al. (2008b)
	Plans for multiple two-family houses	PC	(D)		*2007*		Unk.	
C45	Study to reuse panels of several German PC systems into several small service buildings							Heyn et al. (2008b)
	Small service-building preliminary study	PC	(D)		*2007*		Study	
C46	Reuse of 20 external-wall, 20 internal-wall, and 40 slab panels of the P2 Cottbus PC system from mass housing in a new association house							(Dechantsreiter et al., 2015; Heyn et al., 2008b; Mettke, 2010)
	Kolkwitz association house	PC	Kolkwitz (D)	10	2008		Built	

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Case-study code	Top line: PRECS case-study description Bottom line: (Receiver-) project name	Main concrete type	Receiver-project location (Country)	Approx. distance from donor building in [km]	PRECS case-study date (start)	Component age at receiver construction start (approx.)	Design-solution status	Reference
C47	Reuse of 10 external-wall, 8 internal-wall and 12 slab panels of the P2 PC system from mass housing in a new office building, using a new 15-cm base support to heighten the walls							Heyn et al. (2008b)
	Boxberg office building	*PC*	Boxberg (D)		2008		Unk.	
C48	Several projects to reuse panels of German PC system in new houses							Heyn et al. (2008b)
	Design projects for houses	PC	(D)		2008		Study	
C49	Reuse of slab panels from German PC systems for ditch crossing							Heyn et al. (2008b)
	Ditch crossings	PC	(NL)		2008		Built	
C50	Reuse of panels from *German PC systems* for various agricultural equipment							Heyn et al. (2008b)
	Low silos and bulk material storage walls	PC	(NL)		*2008*		Built	
C51	Reuse of 17 "Inverset" steel-concrete bridge-deck elements from a highway ramp as slabs in a new house							(ArchDaily, 2009; Gorgolewski, 2017)
	Big Dig House	PC	Boston (USA)	*< 40*	2008	55	Built	
C52	Reuse of the panels of three Olympic-village bungalows for *SF* in the relocated bungalows							(Huber, 2013, 2008; zukunftsgeraeusche, 2010)
	"Bestandverplanzung" Pavilion	PC	Munchen (D)		2008	36	Built	
C53	Reuse of 200 panels of the P2 PC system from mass housing in new vacation-resort buildings, but the project was, in 2016, blocked							(Asmus and Mettke, 2014; Dechantsreiter et al., 2015; Rundschau, 2016)
	Santa Fe vacation resort	PC	Casel (D)	30	*2009*		Unk.	
C54	Reuse of CP (slab, internal-walls, external-wall panels, and staircase) of buildings from East-German (PH12 and WBS70 PC systems) and West-German (OLY 72 PC system) buildings in a new exhibition pavilion, with resized CP, testing new reassembly methods and combining simple slabs into cantilever slabs							(Dechantsreiter et al., 2015; Fischer et al., 2012; Huber, 2013; Vogdt et al., 2016)
	"Plattenvereinigung" pavilion	PC	Berlin (D)	600 and 100	2010	40	Built	
C55	Reuse of panels of the BES PC system from lowered mass-housing buildings in new low-rise unheated buildings, encasing panels that had lost their connecting device into new CIP foundations, resizing gable walls, and reusing balcony slabs as roof slabs.							(Hagan, 2013; Hagan and Kontukoski, 2009; Huuhka et al., 2019)
	Raahe garage and garden pavilions	PC	Raahe (FI)	0	2010	22–43	Built	
C56	Master thesis on the reuse of several types of hollow-core slabs from office buildings for SF in multi-family buildings (Master thesis)							Naber (2012)
	Study to reuse hollow-core slabs in multi-family buildings	PC	*Rotterdam (NL)*	*10–50*	2012		Study	
C57	Master thesis on the reuse of several types of hollow-core slabs from office buildings for SF in single-family dwellings (Master thesis)							Naber (2012)
	Study to reuse hollow-core slabs in single-family dwellings	PC	Rotterdam (NL)	*10–50*	2012		Study	
C58	Master thesis on the reuse of precast CP (beams, columns, walls, slabs) from office buildings in new housing projects							Glias (2013)
	The Donor Skelet (Glias)	PC	*Amsterdam (NL)*	*< 60*	2013	24–25	Study	
C59	Reuse of resized panels from mass-housing in two new wall systems implemented in an unheated pavilion							(Bellastock, 2021; Bellastock, 2018; Castaros, 2018; Chantereau, 2017)
	Bellastock Stains pavilion	PC	Stains (F)	0	2016	51	Built	
C60	Reuse of large pieces from a CIP multi-family housing building for a new exhibition pavilion - the pieces are parts of an apartment, with two side walls and the top and bottom slabs, cut further than the walls, moved as one block							(Bremen Bouwadviseurs, 2018; Superlocal, 2018)
	Superlocal exhibition building	*CIP*	Bleijerheide (NL)	0	2017	50	Built	
C61	Reuse of garden tiles from an industrial site to build new walls for a pavilion, combining the garden tiles with new reinforcement bars, left-over concrete mixes and lost formworks							(Borges, 2022; EAST/EPFL, 2019; Meyer, 2018)
	Traverse pavilion	PC	Ecublens (CH)		2018		Built	
C62	Reuse of monolithic floors as slabs into new houses (Master thesis)							Dolkemade (2018)
	Terrace houses with reused slabs	CIP	(NL)		2018		Study	
C63	Master thesis on the design of new connections to reuse components of four typical load-bearing systems							Volkov (2019)
	Study for circular concrete connections	CIP, PC	(NL)		2019		Study	
C64	Master thesis on a computational tool to arrange reusable concrete pieces in new-project facades							(Marshall, 2019; Marshall et al., 2020)
	Marshall computational tool	CIP	(USA)		2019		Study	
C65	Pilot project to reuse large pieces from a CIP multi-family housing building for new housing - the pieces are parts of an apartment, with two side walls and the top and bottom slabs, cut further than the walls, moved as one block							(Hopkinson et al., 2018; Ritzen et al., 2019; Superlocal, 2019, 2020)
	Superlocal circular houses	*CIP*	Bleijerheide (NL)	0	2019	50	Built	
C66	Master thesis on the reuse of cast-in-place columns from office buildings, for example, as brick walls in new buildings							(Strauss, 2021a, 2021b)
	Proposal for reusing cast-in-situ concrete columns as brick walls	CIP	Brussels (B)	<5	2020	46	Study	

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Case-study code	Top line: PRECS case-study description Bottom line: (Receiver-) project name	Main concrete type	Receiver-project location (Country)	Approx. distance from donor building in [km]	PRECS case-study date (start)	Component age at receiver construction start (approx.)	Design-solution status	Reference
C67	Master thesis on the redesign of an existing housing building reusing PC components from office buildings							van den Brink (2020)
	Study for new reused-concrete housing buildings	PC	Eemnes (NL)	30	2020	35	Study	
C68	Reuse of pieces sawn from CIP building and of PC-CP production waste for a new parking pavement							(Comment, 2021; Küpfer et al., 2022)
	Meyrin Car Parking	CIP, PC	Meyrin (CH)	15	2021	various	Built	
C69	Reuse of 25 pieces sawn in CIP walls and foundation mats for a new 10-m-span post-tensioned footbridge prototype							(Devènes, 2021; Devènes et al., 2022b; Küpfer et al., 2022)
	Re:Crete footbridge	CIP	Fribourg (CH)	90	2021	10	Built	
C70	Reuse of two footbridge I-beams as beams in a new footbridge							Arc2 architecten (2021)
	Almere ReUseBrug	PC	Almere (NL)	55	2021		Built	
C71	Reuse of bridge components for SF in the relocated bridge							Implenia (2021)
	Nesbyen second-hand bridge	*PC*	Nesbyen (NL)	135	2021		Unk.	
C72	Reuse of station-platform slabs as paving slabs laid on concrete beams and piles for an outdoor courtyard							(ale_archifre, 2020; Hof van Cartesius, 2021)
	Cartesius courtyard	PC	Utrecht (NL)	30	2021		Built	
C73	Master thesis on the reuse of the CIP and PC structure of a school							Demol (2021)
	Sketches for the reuse of the CIP and PC structure of a school	CIP, PC	(B)		2021		Study	
C74	Pilot project on the reuse of PC bridge girders (keeping or not the CIP slab) in new overpasses							(Vergoossen et al., 2021, 2022)
	Circular overpasses	PC, CIP	(NL)		2021	40	Unk.	
C75	Master thesis on the design of a new structure using reclaimed CIP concrete component including deconstruction and reconstruction planning, reinforcement and connection techniques							Widmer (2022)
	Residential building with reused cast-in-place concrete components	CIP	(CH)		2022		Study	
C76	Reuse of pieces sawn from CIP structures for weight foundations in a new service building							Petersen (2022)
	Hortus foundations	*CIP*	Allschwil (CH)		2022		Unk.	
C77	Reuse of pieces sawn from CIP slabs for new-column foundations in the transformation of an existing building							(bauburoinsitu, 2022; Demierre, 2022)
	Baubüro column foundations	CIP	Zurich (CH)	*<30*	2022	*<40*	Built	

Appendix C. environmental-impact list

Appendix C lists the environmental impacts of PRECS case studies when compared to conventional alternatives, as collected from the records. Computing methods, system boundaries, functional units, and hypotheses are heterogeneous. Non-quantified environmental comparisons are excluded. Environmental indicators account for: CO2 emissions [CO2]; energy use [MJ]; land use [m2?]; oil [l]; global-warming potential [CO2eq]; shadow price [€1]; ecological load [EP]; or environmental costs [€2]. A negative number indicates an environmental-impact reduction of PRECS in comparison with another alternative.

Case-study code	Compared design alternative, as described in the record(s)	Environmental-impact difference [unit]	Source
C20	New cast-in-place concrete building	– **60** [% CO2]; – **40** [% MJ]	Roth and Eklund (2000)
C38	Traditional dike construction	– **30** [% m^2]; – **26** to – **28** [% l]	Mettke (2010)
C46	Non-reuse alternative	– **97** [% CO_2]	Mettke (2017)
C56	New hollow-core slabs (vs 71% reuse)*	– **53** [% CO_2eq]; – **56** [% $€_1$]	Naber (2012)
C57	New hollow-core slabs (vs 69% reuse)*	– **56** [% CO_2eq]; – **50** [% $€_1$]	Naber (2012)
C58	Recycled-concrete house	– **90** [% CO_2eq]; – **75** [% $€_1$]	Glias (2013)
C67	New concrete building	– **46** [% CO_2eq]	van den Brink (2020)
C68	(a) Bituminous surface/(b) Recycled concrete slab	– **81**/– **82** [% CO_2eq]; – **77**/– **65** [% EP]	Küpfer et al. (2022)
C69	Recycled-concrete monolithic arch*	– **63** [% CO_2eq]; – **48** [% EP]	Küpfer et al. (2022)
C74	New concrete girders	– **44** [% CO_2eq]; – **49** [% $€_2$]	Vergoossen et al. (2021)
C75	Conventional cast-in-place structure (vs "Reuse 1")*	– **71%** [% CO_2eq]	Widmer (2022)

* Comparison with other alternatives is additionally available in the same source.

Appendix D. construction-cost list

Appendix D lists the construction cost impacts of PRECS case studies when compared with conventional alternatives, as collected from the records. A negative cost difference indicates cost reduction of PRECS compared to other alternatives, and a positive cost difference indicates a cost increase. Non-quantified cost comparisons are excluded. Computing methods, system boundaries, and hypotheses are heterogeneous.

Case-study code	Country	Date	Compared design alternative, as described in the record(s)	Cost difference [%]	Source
C9	NL	1986	Conventional building	**+ 19**	(Coenen et al., 1990; te Dorsthorst et al., 2000)
C20	S	1997	Conventional construction	**+ 10 to + 15****	(Addis, 2006; Eklund et al., 2003)
C22	D	1999	Conventional construction	**− 15**	(Heyn et al., 2008b)
C24	D	2001	Conventional construction	**− 20; − 15 to − 20**	(Heyn et al., 2008b); (Nationale Stadtentwicklungspolitik, 2017)
C26	S	2002	Conventional building	**+ 10 to + 15****	(Addis, 2006; Eklund et al., 2003)
C28	D	2004	Conventional structure	**− 30**	(Dechantsreiter et al., 2015; Mettke, 2010)
C31	D	2005	Conventional construction	**− 15**	(Heyn et al., 2008b)
C34	D	2006	Conventional construction	**− 25; − 12**	(Heyn et al., 2008b); (WBK21, 2005)
C36	D	2006	Conventional construction	**− 10**	(Heyn et al., 2008b)
C38	D	2006	Conventional construction	**− 10 to − 20**	(Mettke, 2010)
C40	D	2007	Conventional construction	**− 30**	(Heyn et al., 2008b)
C44	D	2007	Houses with new precast elements	**− 12**	(Heyn et al., 2008b)
C53	D	2009	Individual precast elements (various)	**− 25 to − 78**	(Asmus and Mettke, 2014)
C56–C57	NL	2012	New hollow-core slabs	**+ 18 to + 29**	(Naber, 2012)
C58	NL	2013	House with new concrete elements	**− 10**	(Glias, 2013)
C59	F	2016	(a) Brick wall/(b) Concrete block wall	**− 30/+ 35**	(Bellastock, 2018)
C68	CH	2021	(a) Bituminous surface/(b) Recycled-concrete slab	**+ 35/− 5**	(Küpfer et al., 2022)
C69	CH	2021	Recycled-concrete monolithic arch*	**+ 54**	(Küpfer et al., 2022)
C75	CH	2022	Conventional construction (vs "Reuse 1")*	**− 10**	(Widmer, 2022)

* Comparison with other alternatives is additionally available in the same source.

** Compensated by governmental grants (Eklund et al., 2003).

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