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Review article

Taxonomy of design for deconstruction options to enable circular economy in buildings

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ABSTRACT

The construction sector, due to its significant environmental impacts, is a focus area for the promotion of a shift towards the circular economy within the EU. A spotlight has been cast on the necessity to reduce construction and demolition waste and prioritise reuse and high-quality recycling. This work centres on selective demolition and design for deconstruction (DfD) as means of achieving these goals. A literature review is carried out, with the two-fold aim of assessing the state of the art in life cycle assessment studies on this topic and developing a taxonomy of applicable selective demolition and DfD solutions, framing it within the context of policy development in the EU. Available measures are identified for different building structural typologies (concrete, timber, masonry, steel), at the material and element level, providing a comprehensive overview of current and developing technologies. A taxonomy is proposed to support users in the identification of available measures and to link the effects thereof in terms of circularity. A literature-based quantitative assessment of current and potential reuse material rates is provided, together with the greenhouse gases (GHG) emission savings associated with reuse, in order to describe the present situation and highlight the potential for improvement. Reuse potential is found to vary between 0%–80%, depending on material and source; current European reuse rates are estimated <15%. In terms of C-footprint, reuse appears beneficial in most cases. The additional GHG savings from reuse relative to alternative end-of-life options span from 1.30 (gypsum) to 5464 (expanded polystyrene) kg $CO_{2\text{-eq.}}$ per tonne of material managed.

1. Introduction

The building sector has long been identified as a focus area for impact reduction efforts, due to its significant contribution to global energy consumption and greenhouse gas (GHG) emissions, with buildings being responsible for 30%–40% of primary energy consumption and 40%–50% of GHG emissions worldwide (Ramesh et al., 2010; Chau et al., 2015). Within the European Union (EU) in particular, half of all extracted materials and energy consumption and one third of water consumption and waste generation can be attributed to the building sector (Lindblom, 2016; European Commission, Executive Agency for Small and Medium-sized Enterprises, 2021). Efforts to reduce the impact of the building sector at the European level fall within the broader European Green Deal policy framework, aimed at making the EU's economy sustainable in its entirety. The overall goal is for the EU to become climate neutral by 2050, through a series of initiatives covering all sectors of the economy, among which features the construction sector (European Commission, 2020c).

From a policy perspective, several steps have been taken at the EU level to ensure the sustainability of the built environment (Kylili and Fokaides, 2017). A considerable part of past and current policy efforts is focused on the use phase of buildings, as historically this stage of the life cycle of buildings has been shown to be responsible for the highest fraction of environmental impacts (Mastrucci et al., 2017). Policy aimed at reducing energy consumption and its impacts is therefore well developed. One of the most relevant pieces of legislation in this area is constituted by the Energy Performance of Buildings Directive (European Commission, 2010), adopted in 2010 and revised in 2018. Both this and the New Renovation Wave (European Commission, 2020b) largely focus on improving the energy performance of buildings and decarbonising their energy consumption; an unintended consequence of the measures implemented to achieve these goals, however, is the potential for an increase in waste generation. Moreover, as the energy aspect is progressively being taken care of, the relative importance of embodied impacts has been growing; focus is therefore shifting towards material use, with the goal of increasing circularity within the sector. Regulation no. 305/2011 establishes harmonised conditions relative to the marketing of construction products, detailing how to communicate

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their main characteristics and use circular economy markings, effectively working towards the removal of technical barriers within the market (European Commission, 2011). The Waste Framework Directive (European Commission, 2018a) promotes selective demolition (i.e. the deconstruction of buildings following a predefined order, with the goal of increasing material recovery) and aims at reducing waste generation and ensuring that construction and demolition waste is handled in an environmentally sustainable way. Also relevant to the issue of sustainability within the construction sector is the Circular Economy Action Plan (CEAP), one of the main blocks of the European Green Deal, which includes a section specifically dedicated to buildings and construction, with the goal of increasing the longevity and adaptability of buildings, decreasing waste generation throughout their life cycle and leading to an efficient use of resources (European Commission, 2020a; European Commission, Executive Agency for Small and Medium-sized Enterprises, 2021). This policy framework creates a space to investigate measures to promote circularity throughout the life cycle of buildings.

Moving towards a circular economy while building in a sustainable way and decreasing the environmental impacts of the construction sector, all of which are objectives of the aforementioned European Green Deal, must be achieved through a series of measures acting at all stages of a building's life cycle. Design for deconstruction (DfD) has been identified as a relevant strategy to promote circularity and move the construction sector towards the goals mentioned above, particularly in the medium to long term, as it would affect the construction of new buildings, starting from the design phase (European Commission, 2011; Kylili and Fokaides, 2017). Currently, there is no internationally agreed upon definition of design for deconstruction (Kanters, 2018), though the term is broadly used to indicate measures implemented from the design stage and aimed at facilitating the non-destructive deconstruction of a building at its end of life, with the goal of increasing the reuse and recycling potential of selected building elements. Indeed, the ISO 20,887 standard provides an overview of the overarching principles of design for deconstruction and adaptability and describes strategies for the implementation of these principles from the design stage (International Standards Organisation, 2020). In the present work, the terminology *design for deconstruction* is used as a proxy to include a broader selection of terms, such as design for adaptability, design for disassembly, and reversible building design. A glossary of these and other relevant terms used throughout this work is provided in Appendix A. Lack of a shared definition notwithstanding, several reviews are available which focus on the potential practical implementation of DfD measures (Kanters, 2018; Ostapska et al., 2021; Askar et al., 2022; Munaro et al., 2022). However, these tend to focus on general concepts, without an in-depth, cohesive analysis of how these concepts are reflected at the material and element level. This paper aims at filling that gap, by gaining an understanding of the role and handling of common construction materials throughout all life cycle stages, and detailing current end-of-life practice in particular. Through this approach, an overview is provided of the *status quo* (conventional demolition) and areas with potential for improvement are highlighted, with a focus on increased circularity obtainable through the implementation of selective demolition and DfD measures. The assessment is carried out by way of a literature review at the material and element level for a set of four building types, to ensure as comprehensive an analysis as possible. While the review focuses on the EU area, and the collected data are organised in a systematic manner, to develop a taxonomy of selective demolition and DfD measures covering different levels of granularity, which should be broadly applicable also outside the EU. While the main focus of this work is the end of life of buildings, this is tied into all other stages of a building's life cycle. Indeed, improvements at the end-of-life (EoL) stage lead to increased circularity, reducing the amount of raw material needed at the production stage and affecting construction techniques, as well as maintenance and repair during the use phase. DfD in particular affects all life cycle stages, as it involves planning the use and handling of a building and each of its components from the design phase up until the end of their service life. The primary goal of this work is therefore to highlight viable paths to waste reduction within the construction sector, while shining a spotlight on the benefits which can be derived from the reuse of these avoided-waste materials, mainly in terms of a decreased necessity for raw material extraction in new construction projects.

In a future step, it will be desirable to quantify the potential environmental benefits relative to the implementation of selective demolition or DfD options. The present study is thus laying the foundations to facilitate LCA studies focusing on the implementation of DfD measures aimed at reducing its impact through alternative approaches to design and demolition. In its current form, the taxonomy developed in this work should prove useful to systematically classify potential alternatives to increase circularity and reduce waste generation within the construction and demolition sector, by providing a detailed list of options for the handling of each building element and material. The information has been classified in such a way as to make it easily accessible, to facilitate not only the attainment of a general overview, but also the identification of data relative to a specific element belonging to a particular building type. The information collected is valid for both existing buildings (particularly where it concerns conventional and selective demolition) and new buildings, which should, where possible, be designed following appropriate DfD guidelines.

2. Materials and methods

Structural components have a major impact on buildings compared to non-structural ones. Furthermore, while the latter have a shorter life cycle and are generally easier to repair/replace, the structures characterise a building throughout its entire service life. The implication is that a taxonomy of buildings must be based on the structural typology of their components. The Eurocodes, a set of European standards that provide a common approach to the design of buildings and civil engineering works (European Commission, 2023b), already define the structural materials that are assumed as the basis for this work: concrete (EN 1992), steel (EN 1993), timber (EN 1995) and masonry (EN 1996). It should be noted that the Eurocodes also include composite steel and concrete structures (EN 1994) and aluminium structures (EN 1999), which were considered out of scope for the current project. As the present work focuses exclusively on the EU, it was deemed reasonable to use the Eurocodes as a basis for the classification of buildings and their structural materials.

The work is in the form of a literature review and was carried out using Scopus and Google Scholar as main search engines. The keywords, used in different combinations, are the following: *Building*, LCA, recycl*, reuse, DfD, design for deconstruction, design for disassembly, design for reuse, selective demolition*. As the focus area is the EU, entries were manually restricted to reflect this geographical boundary: policy initiatives in particular were limited to the target region, while in terms of selective demolition and DfD strategies, techniques applied elsewhere were at times included, as long as they were also proved to be applicable (potentially with some modifications) in the EU. That is for instance the case of bricks with dry connections, mentioned by Khamidi (2002) in relation to South East Asian markets, but also applied by the Dutch ClickBrick (Wienerberger, 2019).

A preliminary step consisted of assessing the state of the art concerning the analysis of DfD and selective demolition measures in buildings from a life cycle perspective. Following this, an in-depth analysis was carried out to identify DfD and selective demolition measures at the material and element level and compare them to current practice. This part of the work is structured as follows: four building types have been identified, based on their main structural material (concrete, timber, masonry and steel). A table has been created for each of these building types, listing the most common materials that constitute them, divided by building element (such as floor, roof, etc.) and function (structural or non-structural). This first step has been largely based on the work

Table 1
Criteria used to develop the literature review.

Search engines	Scopus, Google Scholar
Keywords	Building*, LCA, recycl*, reuse, DfD, design for deconstruction, design for disassembly, design for reuse, selective demolition.
Literature types	Journal articles, conference papers, book chapters, grey literature and company websites
Years included	2000–2023

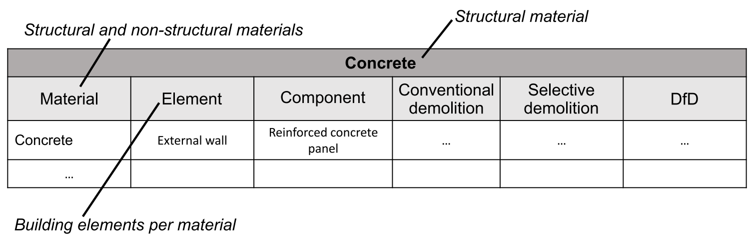

Fig. 1. Basic structure of the output tables developed for each of the four structural building materials. DfD: design for deconstruction.

carried out in the Basket of Products indicator on housing (Baldassarri et al., 2017): concrete, timber and masonry buildings modelled within this project have been analysed and the characteristics common to each type have been collected and used in the relevant table within the present work. Steel buildings, being for the most part commercial buildings, were not included in the Basket of Products, which focuses on the residential stock. For this category, other literature has been used as the main source (Cho et al., 2012; Zygomalas et al., 2013; Zygomalas and Baniotopoulos, 2014; Abd Rashid and Yusoff, 2015; Baldassarri et al., 2017; Eliassen et al., 2019). Once the tables were set up, the literature review was carried out, with the goal of establishing for each material and, whenever possible, each building element, what current practice is (conventional demolition) and what potential improvements might be implemented by way of selective demolition and DfD. Many of the conventional demolition entries were initially filled using as a source of information a 2022 JRC report (Damgaard et al., 2022); this information was later verified and added to through the literature review.

As a first step, the table was filled in with the information found through the system detailed above; in a second step, the search was perfected by focusing on the missing information and carrying out material-specific searches. This meant including the material type as a keyword, as well as broadening the search to include information collected in reports and websites of companies which might implement innovative solutions to handle specific construction materials. Moreover, the review was expanded by including not only the papers directly resulting from the search itself, but also those referenced in the initially selected articles, and which might be relevant to the current work. Only papers published after the year 2000 were considered, to avoid risking the inclusion of potentially outdated information, as well as to account for the fact that interest in selective demolition and DfD has been on the rise in recent years. The analysed documents belonged to different categories: journal articles, conference papers, book chapters, grey literature and company websites. Once the four tables had been filled in, the information they contained was reviewed by the authors. The criteria used to carry out the review have been summarised in Table 1. A total of 117 literary sources and 6 company websites have been used, as shown in the supplementary material (*References* tab).

As information is more readily available in literature at the material level, for each material included in the tables, a General section was created, detailing current practice and potential improvements for the material in question regardless of the specific building element in which it could be found. Immediately below, specific information referring to individual elements is listed, where available. The information detailed in each of the four tables, the structure of which is shown in Fig. 1, is as follows:

- Material, such as timber, glass, copper, etc.
- Function: structural or non-structural.
- Elements: foundations, underground retaining wall, column, floor, stairs, roof, internal wall, external wall, window, door, systems.
- Components: this are sub-elements: for instance, a floor could include a concrete slab, a screed and some type of flooring.
- Conventional demolition: information about current practice.
- Selective demolition: information about whether selective demolition could be implemented and with what results.
- Improved recycling practices: measures to increase the recyclability of a material, element or component; often correlated to selective demolition, as it leads to “cleaner” waste streams.
- DfD: measures that fall under the umbrella of design for deconstruction.
- DfD output: improvement brought about by the implementation of DfD measures compared with the outcome of conventional demolition.
- References: data sources.

Where possible, the information obtained from the review was used to assign a Technology Readiness Level (TRL) to selective demolition and DfD measures, on the basis of the scale adopted within the context of European projects (European Commission, 2014). All conventional demolition measures are understood to have a TRL of 9.

In a subsequent step, a new literature search was carried out, focusing on quantitative aspects related to reuse in the construction sector. The methodology was largely unchanged, though new keywords were used as a starting point: *reuse potential (rate*), potential for reuse, reuse rate**, in combination with *construction* and *building**. A JRC report (Cristóbal et al., 2024) was used as an additional source. Numerical information about current and potential reuse rates was thus collected, and is presented in Section 3.4.

3. Results and discussion

3.1. State of the art – Life cycle assessment

As mentioned above, any comprehensive solution aimed at increasing the overall sustainability of the construction sector should include the entire building life cycle. This is considered necessary to avoid burden-shifting, i.e. to ensure that an improvement at a particular stage of the life of a building does not inadvertently cause a worsening of impacts at another stage, potentially bringing about a worse environmental performance overall. One way of achieving this is by adopting an LCA approach, which makes it possible to account for all phases of the life cycle of a building (i.e., production, construction, use phase, end of life), while calculating its environmental impacts and identifying areas with potential for improvement. The available literature focusing on the use of LCA to evaluate selective demolition and DfD measures is rather fragmented, generally offering insights into specific buildings or materials, without managing to paint a complete picture of the situation on a more general level.

3.1.1. Peculiarity of the construction sector in relation to the overall life cycle of a building

Assessing the environmental impacts of a product throughout its life cycle is a complex matter regardless of the specific industry being analysed, due to the large amount of data required and the necessity to make decisions about the LCA methodology and any assumptions needed to remedy potential data gaps and/or to simplify the system. However, performing an LCA study relative to the construction sector presents some additional challenges when compared to other areas, due to a number of attributes that are characteristic of the building sector in particular (Ortiz et al., 2009; Christensen et al., 2022). The main cause for this added complexity is the service life of buildings, which spans decades and makes it harder to assess their impacts during the whole life cycle, as that would require predicting potential evolutions in markets, technologies and user behaviour in the long-term (Khasreen et al., 2009). The building lifespans used in LCA studies generally range from 25 to 100 years (Sartori and Hestnes, 2007; Khasreen et al., 2009; Ortiz et al., 2009; Ramesh et al., 2010; Sharma et al., 2011), leading to increased uncertainties in the variables used to fully develop the LCA system (Buyle et al., 2013). The large variation in adopted lifespans across different studies also complicates comparisons between studies and contributes to the differences in results emerging from LCA studies. Other factors to be considered include the presence of elements within the building having a lower service life than the building itself; variations in materials and a building's functionality and structure brought about by maintenance and retrofitting; changes in user behaviour over time, which can have a significant effect on the use phase in particular; the large variety of available materials and construction techniques differing not only based on the construction period of a building (due to innovation and new legal requirements), but also on a geographical basis; the uniqueness of each construction project, which often makes it necessary to make decisions on a case-by-case basis. The presence of several different stakeholders also contributes to the complexity of any building sector-specific impact assessment analysis, as it can lead to data discrepancies from one life cycle stage to another: indeed, designers do not produce the components they select to ensure the required building performance, nor do they erect the building themselves (Ortiz et al., 2009; Anand and Amor, 2017; Christensen et al., 2022).

3.1.2. Design for deconstruction

Several reviews with a focus on DfD can be found in literature, though they tend to focus on qualitative aspects, highlighting relevant construction strategies as well as advantages of and challenges to adopting DfD within the current policy and cultural landscape (Kanters, 2018; Ostapska et al., 2021; Askar et al., 2022; Munaro et al., 2022). Ostapska et al. (2021) carried out a literature review on DfD-related studies, dividing the available works into five categories, depending on their main focus: DfD analysis through Building Information Modelling (BIM), tools for DfD assessment and certification, development and/or description of a DfD framework, analysis of the current state of DfD and case studies. The majority of case studies focuses on joints and connections, as these are considered fundamental to enable disassembly of a structure and the potential reuse of its parts. Other case studies analysed existing DfD structures, and a few described DfD concept designs to be implemented. The materials more commonly assessed were found to be steel-concrete for joints and wood (followed by steel and concrete) for structures, though studies were also available focusing on masonry and aluminium. When it comes to quantifying environmental impacts, reviews are not as readily available, though there are several individual case studies on the subject, relying on LCA methodology to carry out the assessment. The studies found during the literature review are listed and described in the supplementary material (*LCA_DfD* tab). The functional unit, when explicitly mentioned, was generally the entire building (Arrigoni et al., 2018) or a square metre of floor area (Densley-Tingley and Davison, 2012; Eberhardt et al., 2019), in line with what is usually the case for LCA studies within the building sector (Ortiz et al., 2009; Buyle et al., 2013). Some studies, however, do not have as a goal assessing an entire building designed for disassembly, but rather a specific building element, such as a wall or floor system. In that case, the functional unit is often a square metre of the element in question (Eckelman et al., 2018; Androsevic et al., 2019), or the element as a whole (Eberhardt et al., 2020). These studies include a variety of different materials, though they address them within the context of a specific case study, rather than on a general level, thus limiting the amount of information which can be extracted and applied to other contexts. Concrete and steel, being rather ubiquitous structural materials, appear in several works, as does, to a lesser extent, timber (Densley-Tingley and Davison, 2012; Akbarnezhad et al., 2014a; Arrigoni et al., 2018; Eckelman et al., 2018; Xia et al., 2020); however, other non-structural materials are also considered, such as rock wool, polyethylene foil, gypsum (Androsevic et al., 2019), bitumen, glass, aluminium and bricks (Eberhardt et al., 2020, 2021). The service lives considered span from 6 months, for a temporary pavilion (Arrigoni et al., 2018), to 80 years (Eberhardt et al., 2019), with some studies accounting for a first and second life for the building (Arrigoni et al., 2018; Eberhardt et al., 2019) or up to three lives for specific building elements (Eberhardt et al., 2020). In terms of life cycle stages, the majority of the works include the whole life cycle, from the product stage to the EoL (Densley-Tingley and Davison, 2012; Akbarnezhad et al., 2014b; Arrigoni et al., 2018; Androsevic et al., 2019), with some studies including benefits associated to material recovery (Eberhardt et al., 2019, 2021). In a few cases, the focus is only on specific life cycle stages instead: Eberhardt et al. (2020) only consider production and end of life, for instance, while Xiao et al. (2021) adopt a cradle-to-gate approach, focusing only on the production and transportation phases. Significant differences emerge when looking at the impact categories included in the assessment: global warming impact (GHG emissions) is the most commonly used metric, and in several cases that is the only indicator used (Eberhardt et al., 2020, 2021; Xiao et al., 2021). Other studies include a larger variety of impact categories, such as abiotic depletion potential, acidification, eutrophication, photochemical ozone formation, human toxicity, marine ecotoxicity and freshwater ecotoxicity (Arrigoni et al., 2018; Eckelman et al., 2018; Androsevic et al., 2019; Eberhardt et al., 2019; Xia et al., 2020). Some studies also include additional indicators, such as cost (Akbarnezhad et al., 2014a) or amount of non-hazardous waste disposed (Androsevic et al., 2019). One issue emerging in studies on DfD structures and elements, which tend to have more than one life, is the allocation method to be used. Indeed, according to Densley-Tingley and Davison (2012), one of the major challenges of applying LCA to reusable materials is deciding how the environmental impacts should be shared among the different lives. However, only a fraction of the works assessed explicitly mention the methodology they adopted. Densley-Tingley and Davison (2012) analyse several possibilities, finally choosing to divide total GHG emissions (use phase excluded) by the number of expected lives of the product. Arrigoni et al. (2018) adopt a cut-off approach, meaning that raw material production is attributed to the first life, waste producers bear the burden of waste treatment and recycled products are available burden-free to the consumers, thus promoting their use (Ecoinvent, 2023). Eberhardt et al. (2019) apply a mixed 0:100 and 50:50 allocation approach: in case of non-reusable materials and elements, all impacts are allocated to the first product system (i.e., the first life of the product), while for reusable materials, impacts are divided equally between the two service lives considered. Xia et al.

(2020) implement a non-linear allocation based on the degradation rate of concrete. Eberhardt et al. (2020) compare four different allocation approaches, finally developing a fifth one, based on two parameters: the number of useful lives and a factor indicating how much of the impact is allocated to the first with respect to subsequent ones. The variety of methods used across the different studies makes it extremely difficult to carry out a detailed comparison of the results; moreover, the majority of the studies analysed focus on a specific building or building element, which limits the applicability of the information they obtain to a larger context. However, they address common issues in DfD-related LCA studies, such as the allocation methodology, and cover different scales (from the element to the building level), proving useful in granting a first understanding of the potential advantages and disadvantages of DfD.

In terms of results, Densley-Tingley and Davison (2012) find that a DfD building has slightly lower CO_2 emissions in practically all stages of its life cycle. According to Akbarnezhad et al. (2014a), DfD implementation has lower costs, and embodied energy and carbon values when accounting for a second service life of the structure, though they also assert that the economic and environmental impacts of DfD applications can undergo significant project-specific variations. Arrigoni et al. (2018) states that the environmental impacts of a DfD structure tend to be lower if its second life is predefined, while if that is not the case, the dismantling costs might be higher, making the process disadvantageous. Moreover, according to this study, one of the main parameters to take into account to ensure that DfD implementation is beneficial is the environmental cost of transportation, which risks offsetting that of the component production. Androsevic et al. (2019) finds that the DfD wall they are analysing has slightly lower environmental impacts in most categories. Overall, the results of a DfD analysis vary significantly depending on the specific context and conditions under which it is developed. The dismantling process in particular is key, as it leads to increased material and component recovery, but also tends to have higher monetary and energy costs.

3.1.3. Selective demolition

Several LCA case studies focusing on selective demolition have also been found, including both assessments of partial demolitions and more advanced separations of building components. They are listed and described in the supplementary material (*LCA_SelDem* tab). What emerges is a certain variation in terms of geographical scope: there are works which only analyse a specific element (Andersen et al., 2022), others which look at an entire building (Vitale et al., 2017; Ruggeri et al., 2019; Pantini and Rigamonti, 2020) and others still which include a larger area (a region, to be precise) within their boundaries (Iodice et al., 2021). In terms of functional units, some studies make choices in line with those common in DfD LCA works as well: Pantini and Rigamonti (2020) use one square metre of floor area, and (Andersen et al., 2022) use one square metre of the one element they are analysing (steel façade cladding). Vitale et al. (2017) rely on the net useable area of the building, while Iodice et al. (2021) consider one tonne of construction and demolition waste (CDW) generated within the region under assessment. None of the analysed studies include the entire life cycle in their scope; for the most part, they were limited to the EoL stage and, in some cases, the production stages (Vitale et al., 2017; Ruggeri et al., 2019; Pantini and Rigamonti, 2020; Iodice et al., 2021; Andersen et al., 2022). All studies mentioned in the current section included a variety of midpoint impact indicators, with the exception of Christensen et al. (2022), who only calculated the carbon footprint. Iodice et al. (2021) went one step further and also included endpoint calculations for five areas of protection: prosperity, human well-being, human health, ecosystem health and natural resources. Finally, to circumvent the allocation problem, most studies used the system expansion method (Vitale et al., 2017; Ruggeri et al., 2019; Pantini and Rigamonti, 2020; Iodice et al., 2021; Andersen et al., 2022). Overall, we observe that there is a convergence in the use of system expansion to avoid allocation but there are differences in terms of functional unit and indicators assessed.

Given the differences in methodology, it can be difficult to draw a straightforward comparison among the studies in terms of results. It is established that selective demolition generally has a higher energy consumption when it comes to the deconstruction work (Bayram and Greiff, 2023). Pantini and Rigamonti (2020) find that implementing it did not generate environmental and energy savings for their case study, as the increasing recycling derived from the practice and the subsequent avoided extraction of raw materials were not sufficient to overcome the impacts associated with the demolition activities, waste transport and recycling process. Iodice et al. (2021), on the other hand, come to the conclusion that selective demolition can generate environmental and social benefits, with respect to conventional demolition, but that the increased costs linked to the practice might hinder its implementation. Andersen et al. (2022) also find that conventional demolition has higher environmental impacts across the building life cycle, but that, when assessing only the demolition process, the impacts of selective demolition tend to be higher, largely due to the longer operating times of the necessary machinery. This overview indicates that the feasibility of selective demolition is dependent on the context in which it is carried out, as is the case for DfD.

3.2. Taxonomy

From the analysis of the state of the art in LCA, there emerges a lack of systematisation where DfD and selective demolition (and, more generally, the construction sector) are concerned. The following step was therefore trying to develop a comprehensive database of conventional demolition, selective demolition and DfD solutions at different levels of detail (from material to element). The full taxonomy is detailed in four Excel tables, made available in the supplementary material (together with a list of all documents used for the literature review); the goal of this section is to give an overview of the information contained therein. The effects of implementing selective demolition and DfD, as compared to conventional demolition, are shown in Fig. 2: these approaches broaden the range of EoL solutions available and increase circularity within the building sector, affecting different stages of the life cycle of a building. Selective demolition is implemented at the end of life of a building, and therefore particularly affects the way CDW is handled. The subsequent waste reduction and increased material recyclability is reflected in a wider set of options being opened in the construction of new buildings using the recovered materials. Considering the waste hierarchy at the foundation of the European Waste Framework Directive (European Parliament and Council, 2008), selective demolition mainly acts at the levels of recovery and recycling, at times reaching the second-highest level, that of preparation for reuse. DfD, on the other hand, has to be applied starting from the design phase, and as such, it has an impact on all stages of a building's life cycle. This means that it has a larger potential for circularity, acting at the top of the waste pyramid by preventing waste generation and facilitating (preparation for) reuse. By intervening at the EoL of a building (selective demolition), therefore, the benefits to be obtained during a second life of a material or component are limited (Fig. 2b), particularly when contrasted with the wider opportunities afforded by acting at the conception of the building (DfD, Fig. 2c).

The advantages associated generally associated to the implementation of selective demolition and DfD relate mainly to increased sustainability, by way of reduced waste generation and resource consumption. While these strategies have the potential to significantly contribute to a shift towards a circular economy, however, they are also often accompanied by increased costs. Coelho and De Brito (2011) find that, for a case study in Portugal, conventional demolition tends to have lower costs, but selective demolition might be the more economically viable choice when considering downstream revenues from material sale; this is further confirmed by the literature review carried out in their paper.

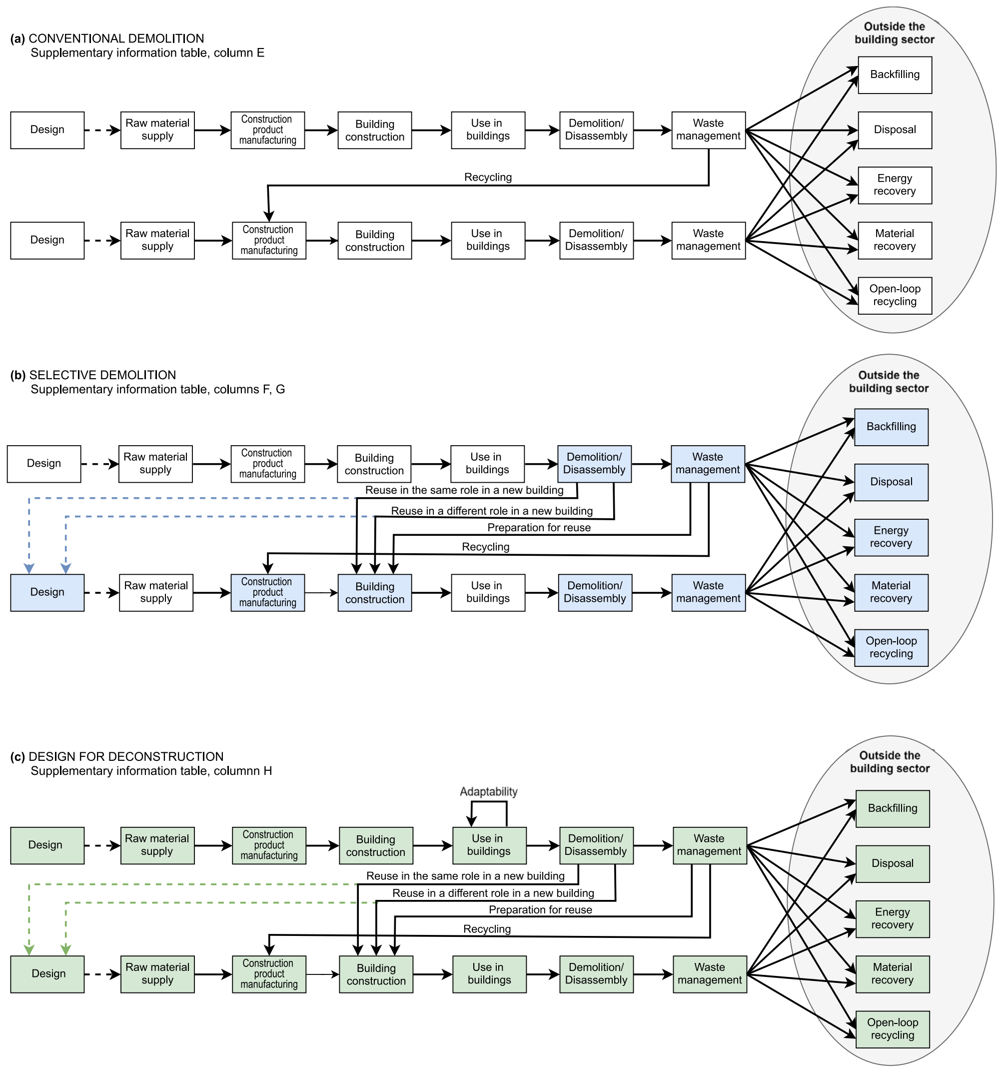

Fig. 2. Stages of the life cycle of a building, with a particular focus on the end-of-life phase, represented in case of (**a**) conventional demolition; (**b**) selective demolition and (**c**) design for deconstruction. Boxes with a background colour represent those stages which are affected by the implementation of selective demolition and DfD measures relative to conventional demolition. Two life cycles are shown for each case to illustrate the consequences of these approaches. Dashed lines represent flows of information, rather than material.

Selective demolition generally has higher labour costs, largely due to the potential need for specialised labour and the longer times needed to complete a job (Iodice et al., 2021) suggest a cost of >6 EUR t^{-1} for selective versus ∼1 EUR t^{-1} for conventional demolition). Yet, where there is a developed market for reused or reprocessed components, the additional costs might be compensated for by the increased sale of recovered materials (Christensen et al., 2022) or reduced expenses for the acquisition of new building materials when the construction company is also performing deconstruction (Ghisellini et al., 2018). The economic feasibility of these measures is therefore highly dependent on the specific context in which they take place, and a life cycle costing approach might be needed to accurately assess it.

The main difference among the four tables is related to the structural materials on which they are focused; the other, non-structural materials, are largely the same across building types, though they might be found in different amounts and configurations. It was found that there are selective demolition and/or DfD measures available to be undertaken for most materials, at least on a theoretical level. Information at the element and component level, however, tends to be scarce. Furthermore, it is sometimes the case that the measures listed in the table refer to niche applications, with limited feasibility at a larger scale (e.g., the reclamation of bricks from demolished masonry walls, as described in cell E5 of the *Masonry* tab, in the supplementary information table). Materials which have been shown to maintain their technical characteristics during laboratory tests (TRL4) might not be guaranteed to do so in other, less controlled environments, meaning that further testing might be necessary for them to become widely used (TRL5-7). This is particularly true where recycling practices are concerned; that is the case, for instance, of the Advanced Dry Recovery technology developed to extract the fine and coarse fractions in waste concrete, so that the latter can be directly recycled, while the former must be processed further (supplementary information table, *Concrete* tab, cell G3). A similar concern is often associated with selective demolition, which includes measures meant to be at least partially applicable to existing buildings; though several selective demolition studies have been carried out on real construction sites, the unique configuration of each building makes it difficult to draw general conclusions and sometimes leads to a discrepancy between what should be possible in theory and what can be done in practice. Even when applications appear promising from a purely technical perspective, there might be obstacles to their implementations, be they cultural or economical. Overall, a major challenge is for recycled or reused materials to be able to meet the technical requirements imposed by European or national regulations. That is the case for the production of structural concrete with recycled aggregate (supplementary information table, *Concrete* tab, cells F3 and G3). Other cases are the reuse of timber derived from

Table 2
Number of sources per material, as obtained during the literature review. PVC: polyvinyl chloride.

Material	Number of sources
Concrete	37
Masonry	20
Steel	36
Timber	43
Aluminium	3
Bitumen	7
Ceramic	5
Copper	1
Glass	10
Gypsum	23
Insulation	11
PVC	5

selective demolition for structural purposes (supplementary information table, *Timber* tab, cell F3), or the reclamation of used bricks from demolished masonry walls (supplementary information table, *Masonry* tab, cell E5). The existence of studies focusing on these sort of recovery opportunities, however, shows a continued and growing interest in the development of sustainable solutions at the material and element level within the construction sector. DfD measures are mainly applicable to new construction and could therefore be more easily implemented on a general level. While the specifics are different for each material, a set of general recommendations can be formulated. They mostly concern the use of appropriate connections (few, visible and reversible), to allow different components to be dismantled without damage, and the adoption of modularity in construction, to increase the reusability of selected components and the potential for off-site construction. In addition to the material-related information contained in the table, other measures should be in place to favour reuse and recycling; namely, a deconstruction plan should be already devised during the design stage, effective communication channels should be created and maintained among the different stakeholders involved in the life cycle of the building, and a standard should be devised to facilitate the storage and transfer of information. With regards to the latter point, it is worth mentioning that an effort is being made at the European Level, by way of the proposed Digital Product Passports (DPP), intended as a way of collecting and sharing data relative to a product across its lifecycle, with the goal of promoting a shift towards the circular economy (Beanland, 2023). DPP are only one of the digital tools either in place or under development which could contribute to the implementation of DfD, and circularity measures in general. Digital building logbooks represent another valuable instrument: they are repositories of building data, recording major events occurring during a building's lifecycle and promoting transparency and information sharing among stakeholders (Volt et al., 2020). DfD can also be aided by BIM tools: the integration of BIM and DfD is a topic of increasing interest, though it is not yet established practice, as it is considered a significant opportunity for sustainable deconstruction, with the ability to provide a solid basis for building data analysis (Akanbi et al., 2019; Akbarieh et al., 2020; Abrishami and Martín-Durán, 2021; Obi et al., 2021; Aziminezhad and Taherkhani, 2023). Digital tools can actively contribute to the development of a circular building sector by providing platforms for open communication among stakeholders and EoL impact analysis.

3.3. Results per construction material

The number of sources found during the literature review and referring to each building material is listed in Table 2.

As mentioned above, measures to improve current practice can be found, albeit at different development stages, for most building materials. The main exception is constituted by metals, such as steel and copper, the recycling of which is already carried out on a large scale, and for which few improvements can be proposed. However, there is ample potential for implementing DfD measures, particularly where steel is concerned: options can be found for reuse at different scales, from constituent products to entire metal structures. A summary of the information relative to the four structural materials is shown in Table 3. Selective demolition outcomes mainly include aggregate production (concrete and masonry), recycling (steel, timber) and partial reuse (brick, steel, timber); DfD measures largely consist of modular construction, use of precast elements and dry connections, leading to varying levels of reuse.

3.3.1. Timber

There are several ways of handling wood waste following conventional demolition: timber can be landfilled or used for energy recovery (by way of incineration or pellet production); it can also undergo open-loop recycling (production of blow-in insulation, such as timber flakes or fibres) or closed-loop recycling (production of particleboards).

Selective demolition can lead to improved waste handling. It is important that timber components are kept intact whenever possible during the dismantling phase, to increase their reuse potential. Depending on their size and damage level, wooden components can be directly reused as structural components, such as columns and beams, reprocessed into smaller components, recycled into glued laminated products and particleboards, or used for energy recovery (supplementary information table, *Timber* tab, cells F3, F4). While wooden elements can be salvaged to some extent, whether the construction system is lightweight or heavyweight (both in load-bearing and non-load-bearing elements), solid timber constructions show limitations in their efficient reuse due to difficulties in resizing the cross-laminated timber panels. In general, large wooden elements designed for key structural roles can be difficult to cascade in a recycling process as they are often attached to other materials, such as insulation, which cannot always be easily removed. However, the removal of external impurities can make it feasible to reuse smaller sections for non-structural uses, thus reducing the need for virgin wood. Conversely, smaller elements are more easily damaged during the demolition process and are therefore more likely to be recycled than reused. Damaged timber can in some cases be cleaned and repaired, to then be reused; reintegrating CDW timber into new construction has the potential to reduce resource consumption, leading to increased circularity. However, there are often economic barriers to this process, suggesting the need deconstruction measures to be imposed, or economic incentives to be offered (Densley-Tingley, 2012; Klinge et al., 2019).

Specific building elements can be more or less suitable for recycling and reuse following selective demolition. Where floors are concerned, nailed or floating installations can potentially be reclaimed, as they can be removed using non-destructive techniques. However, it is possible that wooden components in floors and ceilings might be recovered in poor conditions, thus only being suitable for recycling or energy recovery (supplementary information table, *Timber* tab, cell F5). In walls, wood is often combined with other materials, such as insulation. As a consequence, recovering it without damage and with only minor impurities can be challenging, meaning that recycling might be the best available option. Exterior cladding and interior panelling can be reclaimed if no glue has been used (i.e., if appropriate connection types have been employed) and if the layer of paint that is often present can be removed. Under these conditions, the cladding can be cascaded into secondary board products, such as flooring boards, siding and panelling (supplementary information table, *Timber* tab, cells F9, F12).

DfD can be applied to both lightweight and heavyweight construction systems, albeit in different manners: in lightweight construction, reversibility generally characterises single elements (e.g., walls, floors), while heavyweight construction (based on cross-laminated timber panels) can be reversible at the single element level or for three-dimensional modules (supplementary information table, *Timber* tab, cell H3). DfD is made possible through a series of measures which facilitate reuse, such as prefabrication and modularity; indeed, prefabrication could reduce the timber waste by 65 to 80% (Jahan et al.,

Table 3
Summary of conventional demolition, selective demolition and DfD measures for the four structural materials considered in the study. The conventional and selective demolition columns only contain information about the EOL of the material, while the DfD column also contains a summary of measures to adopt from the design stage to ensure deconstructability.

Material	Conventional demolition	Selective demolition	Design for deconstruction
Reinforced concrete	• Aggregate production (backfilling, road construction, environmental reclamation)	• Aggregate production (high-quality; new structural concrete)	• Modular construction • Precast elements • Dry mounting jointing methods • Reuse
Masonry	• Aggregate production (backfilling, road construction, environmental reclamation) • Landfilling	• Aggregate production (high-quality but low strength) • Reclamation of solid bricks bonded with soft mortars: reuse (non-structural applications) (niche application)	• Dry masonry (no mortar) • Modular construction • Prefabrication • Reuse
Steel	• Recycling	• Recycling • Partial reuse selected components	• Modular construction • Prefabrication • Bolted connections/ limitation of welded parts • Reuse of whole structure, specific components, or constituent products
Timber	• Incineration with energy recovery. • Closed-loop recycling (particleboards, blow-in insulation) • Landfilling	• Component reuse, reprocessing, or recycling	• Modular construction • Prefabrication • Bolts and steel plate connectors (mechanical); no hidden joints • Reuse

2022). Modular construction in particular can refer to planar elements (floor units, walls) or volumes (boxes containing one or several rooms, often including electric and plumbing installations); the adaptability potential of modular volumetric systems is limited; future alterations are easier to carry out for planar elements, constructed using light-timber framing. Other important factors in DfD are the use of specific types of connections (bolts and metal plate connectors, mechanical connections), which facilitate deconstruction limiting potential damage to elements and components; the use of standard sizes for wooden elements, to make substitution and reuse in different applications easier; the lack of pollutants, preservatives, adhesives and, in general unnecessary treatments and finishes, in order to enable direct reuse. Overall, DfD measures aim at facilitating the removal of the building elements in the best possible conditions (i.e., clean and undamaged) to facilitate reuse and reduce the costs associated with the deconstruction itself and the reprocessing of the material, which, if too high, risk rendering the process or recovering and reusing materials financially disadvantageous.

DfD measures are easier to apply to some specific building elements than others. Where floors are concerned, for instance, an effective solution is to use easy-to-disassemble floating floors. On the other hand, in most cases it is better to avoid employing composite systems, unless they have been specifically designed to make the separation of the different materials easy to perform. It is also advisable to avoid treating floors with paints containing heavy metals, to reduce contamination and increase the reusability potential (supplementary information table, *Timber* tab, cell H5). This last note also applies to wall materials: the wooden components can be reused or recycled, as long as they have not been contaminated by toxic preservatives, paint or adhesives (supplementary information table, *Timber* tab, cell H8). Where interior cladding in particular is concerned, finishes should be done with wax or natural stains instead. Nails in cladding should also be replaced with removable screws whenever possible, to facilitate disassembly without damage to the wood (supplementary information table, *Timber* tab, cell H9).

3.3.2. *Masonry*

Following conventional demolition, bricks are often crushed and, together with other inert materials, used to produce recycled aggregates for backfilling purposes and for base and sub-base road construction. Alternatively, they can be disposed of in a landfill (Damgaard et al., 2022).

With the implementation of selective demolition (supplementary information table, *Masonry* tab, cell F3), the number of impurities is reduced and it is possible to use brick to produce high-quality aggregates, which might in turn be used for structural concrete production (though that is not yet considered feasible at a large scale). The fine fraction obtained during the recycling process could be used as recycled aggregate to produce masonry mortar; this, however, is still a niche application. According to Seco et al. (2018), it would also be possible to use clay bricks to substitute up to 30% of clay soil in the production of unfired bricks (TRL4). Furthermore, where soft mortars (lime, clay, ash) have been used, it is possible to separate and reuse the bricks; however, the process can be labour intensive and the reclaimed bricks can mainly be used for non-structural purposes. Hollow brick walls, however, tend to break during disassembly and therefore cannot be easily reused (supplementary information table, *Masonry* tab, cell F7).

The main DfD strategy (supplementary information table, *Masonry* tab, cell H3), where masonry is concerned, is the implementation of mortar-free structures, built through dry-stacking systems (i.e. by using steel plates and wall ties to connect the bricks) (TRL7-8) (Khamidi, 2002; Khamidi et al., 2004; Khamidi, 2006a). This increases the reusability of the bricks, as does the prefabrication of modular units and the lack of grouted reinforcements.

3.3.3. *Concrete*

Following conventional demolition, concrete waste is generally used in the production of recycled aggregates, which are then often employed for backfilling purposes and for base and sub-base road construction. If the concrete is contaminated (e.g., in the case of polystyrene boards used to create voids, gypsum plasters), it should instead be sent to landfill disposal.

Selective demolition (supplementary information table, *Concrete* tab, cell F3) can lead to an increased quality of the inert waste and improved recycling practices, enabling the production of recycled aggregate to be used in structural concrete. An innovative technology, Advanced Dry Recovery, would improve the recyclability of concrete waste by effectively separating mortar from concrete, leading to the attainment of high-quality recycled aggregates; specifically, this system leads to the extraction of three fractions, one coarse and two fine. The recycled coarse fraction can then be used for the production of new concrete (supplementary information table, *Concrete* tab, cell G3). Advanced Dry Recovery's TRL is between 7 and 9, according to different sources (Tecnalia, 2021; European Commission, 2023a). A second innovative technology, Heating-Air classification System (TRL4-7), can be used to further separate the two fine Advanced Dry Recovery output fractions, eliminating small contaminants and leaving mostly ultrafine cement particles to be recycled. Moreover, the fine fraction obtained from the recycling process, often sent to landfill, can instead be used as sand in the production of new masonry mortar (Gebremariam et al., 2020). According to an experimental study, fine recycled aggregate obtained from concrete waste can also be used to produce new bricks, substituting up to 50% of clay soil in the production of unfired bricks (Seco et al., 2018).

Concrete, and reinforced concrete in particular, is difficult to deconstruct unless it has been specifically designed for it: DfD is therefore necessary to enable reuse (supplementary information table, *Concrete* tab, cell H3). Two related solutions that can facilitate disassembly and reuse are modular construction and prefabrication (i.e., the use of precast concrete elements). Several concrete elements can be prefabricated, including stairs, concrete frames, retaining walls and façades. DfD can make it possible to reuse elements like columns, beams, roof and floor hollow core slabs and core walls. As was the case for timber elements, disassembly can be facilitated by selecting the appropriate type of connection at the design and construction stages; specifically, dry mounting jointing methods (removable mechanical fasteners) are recommended.

DfD can have varying results on different building elements. Precast columns and beams can be recovered through deconstruction and subsequently reused; however, an established market is lacking (supplementary information table, *Concrete* tab, cell H6). In concrete floor systems, using the right type of joint can enable reuse, while cast-in-place topping slabs over precast floor members should be avoided (supplementary information table, *Concrete* tab, cell H8). Facades made of precast concrete can also be reused, provided that suitable connection types, such as stainless steel connections and removable fasteners, are employed. It is also possible to build DfD walls by using interlocking concrete blocks, which do not require mortar and can be used in modular construction (supplementary information table, *Concrete* tab, cell H12).

3.3.4. Steel

In current practice, virtually all steel is recycled, limiting the need for potential improvements on that front (supplementary information table, *Steel* tab, cell E3). However, by implementing selective demolition it is possible to enable partial reuse of selected components, such as purlins, columns and rafters (supplementary information table, *Steel* tab, cell F3). In general, hot rolled sections have higher reusability potential than trusses and welded-tapered sections.

Depending on the degree of DfD, reuse can be enabled to different extents: in-situ reuse without removing the components from the structure; reuse of the whole structure; reuse of specific building components; reuse of constituent products (supplementary information table, *Steel* tab, cell H3). Prefabrication and modular construction are once again effective strategies to enable reuse, while fire protection chemicals might somewhat complicate the process by contaminating the steel; however, there are cases in which these substances can be safely removed (e.g. vermiculite-based plaster is removable from a steel structure by way of sandblasting). Bolted connections are recommended if the goal is to be able to reuse a steel structure, as they facilitate disassembly.

3.3.5. Other non-structural components

3.3.5.1. Glass. Glass is commonly present in buildings in the form of windows and curtain walls. Following conventional demolition, glass can be crushed together with other building materials and landfilled, incinerated or recovered for low-grade applications (e.g., glass cullet can effectively be used in the production of recycled aggregates for road constructions). Flat glass is also often recycled into container glass or, less commonly, into new flat glass; indeed, newly produced flat glass can contain up to 40% recycled material (supplementary information table, *Timber* tab, cell E27).

Where selective demolition is employed, glass is generally separated from the window frame and recycled; this reduces the quantity of contaminants and facilitates the use of recycled glass for the production of new flat glass. It is also possible to use glass waste to produce new glass wool, as this insulation material can contain up to 90% of recycled glass cullet. Provided that the connection type allows for the window to be dismantled without damage, modern, high-performance glass units can sometimes be reused; however, this is a niche application. Repurposing is also a possibility: the glass could be used for indoor applications, which do not require high thermal standards (supplementary information table, *Timber* tab, cell F27).

As for DfD strategies, using dry connection methods (e.g., window beads, TRL9) to connect the glass to the window frame facilitates deconstruction and, in some cases, enables reuse (supplementary information table, *Timber* tab, cell H27). Due to its fragility, however, glass has a limited reuse potential, as it is difficult to ensure that it will not incur any damages during disassembly and transportation. Therefore, even in the case of DfD, recycling is the most common solution and little improvement potential is expected.

3.3.5.2. Gypsum. In current practice, gypsum is generally landfilled. However, gypsum plasterboards can also be recycled (used for production of new plasterboards, in cement production or as a soil improver); this applies in particular to basic panels, which do not contain a variety of other materials (supplementary information table, *Concrete* tab, cell E31).

Landfilling remains a common solution for plasterboard handling even when selective demolition is applied, largely due to economic barriers (supplementary information table, *Concrete* tab, cell F31): in general, i) it tends to be too costly to recycle the material, in large part due to the necessity of adhering to purity level requirements and, ii) in regions with high rate of incineration, there is competition of the gypsum ($CaSO_4$ hydrated) recovered as byproduct at incinerator's flue-gas-cleaning, which creates excess of supply thus dropping (locally) the price and making recycling not competitive. Additionally, transportation costs can also have an impact on the economic viability of plasterboard recycling (Damgaard et al., 2022). However, from a technical perspective, selective demolition facilitates recycling (i.e., using plasterboard in new plasterboard or for cement production), by providing better waste segregation. Selective removal of gypsum plaster, on the other hand, is rather labour-intensive and it is mainly undertaken with the goal of recycling the stony fraction of the construction and demolition waste (i.e., the waste fraction composed of concrete, ceramics and aggregates), rather than the gypsum itself. However, from a purely technical perspective, gypsum is endlessly recyclable, though a percentage of virgin material is necessary during the recycling process to ensure the required purity level. Recycling rates are nonetheless quite low at the European level, being estimated at 10% in 2017 (European Commission, 2017), and economic incentives or penalties might be needed to increase them. One particular issue affecting the market for recycled gypsum is the relative availability of flue gas desulphurisation gypsum, a synthetic gypsum obtained as a result of the sulphur removal process applied to gases derived from coal-fired power plants and municipal solid waste incineration plants (Ladwig, 2006).

Precast gypsum plasterboards are easily assembled within a building and later dismantled; however, it can be difficult to separate their components (gypsum, paper lining and any impurities) (Jiménez Rivero et al., 2016). Implementing DfD measures (dry construction) can contribute to reducing impurities and increasing the recyclability of the material (supplementary information table, *Concrete* tab, cell H31).

3.3.5.3. Ceramic. Ceramic generally undergoes the same processes illustrated for clay bricks in the masonry section. Following conventional demolition, it is normally used to produce low-quality aggregate for road construction (supplementary information table, *Concrete* tab, cell E35). Selective demolition can lead to better recycling practices and the generation of higher-quality aggregate to be used in concrete production (supplementary information table, *Concrete* tab, cells F35, G35). Specific ceramic elements, such as floor tiles and sanitary ceramics, can sometimes be reclaimed through selective demolition. DfD solutions can be implemented for selected components, such as floating floors, enabling reuse (supplementary information table, *Concrete* tab, cell H36).

3.3.5.4. Bitumen. Bitumen is often used for roof covers and waterproof membranes. Following conventional demolition, it is generally landfilled, used for energy recovery or entered into an open-loop recycling process for asphalt production (supplementary information table, *Concrete* tab, cell E38). Selectively collected bitumen is still often used for energy recovery or recycled for asphalt production; however, it can also be used in the production of new roofing felt (TRL7-8) (supplementary information table, *Concrete* tab, cell F38). This application is also an end-goal of employing DfD (supplementary information table, *Concrete* tab, cell H38).

3.3.5.5. Polyvinyl chloride (PVC). In current practice, soft PVC is often recycled to produce roofing sheets, while hard PVC tends to be recycled to PVC dust, chips and granulate. Alternatively, PVC can be used for energy recovery, or be disposed of in a landfill (supplementary information table, *Concrete* tab, cell E40). PVC pipes specifically can be recycled into granulate which is then used in the production of new pipes. Selective demolition (supplementary information table, *Concrete* tab, cell F40) generally leads to increased recycling rates and better recycled material quality. Window profiles in particular can be recycled and used in the production of new profiles, though this is a niche application (supplementary information table, *Concrete* tab, cells F41, H41).

3.3.5.6. Insulation. Insulation as a category includes a large variety of materials, which can be broadly classified into inorganic (e.g., glass wool, rock wool) and organic. The latter can be further categorised into two subgroups, based on their origin: natural (e.g., cellulose, cork) and petrochemical (e.g., expanded polystyrene EPS, extruded polystyrene XPS, polyurethane PUR, urea formaldehyde UF). For the purposes of assessing the end-of-life handling, this classification is adapted to include three insulation groups: the inorganic category remains unchanged; natural organic materials are now defined as organic, and petrochemical organic materials are defined as polymer-based materials (Durakovic et al., 2020; Damgaard et al., 2022). Following conventional demolition, inorganic (mineral) insulation can be recycled in the brick industry (specifically, it can be used in the production of masonry mortar) or, if the presence of contaminants makes that unfeasible, it can be landfilled; polymer-based insulation tends to undergo landfilling or incineration; bio-based insulation is normally incinerated or composted (supplementary information table, *Concrete* tab, cell E43).

Organic and polymer-based insulation is often difficult to dismantle; however, selective demolition can still lead to increased recycling rates (supplementary information table, *Concrete* tab, cell F43). It can also enable reclamation of rigid foam insulation (EPS, XPS). EPS can go through closed-loop recycling, to produce new insulation, or open-loop recycling, to produce lightweight concrete, car parts, etc. Composite insulation panels composed of mineral wool and steel can be dismantled, the materials can be separated and recycled separately and in their entirety; new mineral wool and steel can be produced and then used to produce new composite panels. A similar concept can be applied to composite polyurethane panels: the different panel components can be separated and either recycled (metal) or used for energy recovery (PU foam).

Where insulation is concerned, DfD can be applied to select the most appropriate insulating materials and technologies, to enable recycling and, where possible, reuse (supplementary information table, *Concrete* tab, cell H43). For instance, sprayed insulation (e.g., cellulose fibre, urea formaldehyde) should be avoided, as it is difficult to salvage during deconstruction. On the other hand, blown insulation can be safely extracted using appropriate techniques. Additionally, both rigid and flexible slab insulation solutions can be reused, though from a practical perspective it is easier to reuse the latter, as rigid slabs are more easily damaged during the deconstruction process.

3.3.5.7. Other metals. Metals are normally effectively recycled, leaving little room for improvement in current practice. That is the case for copper, which is used in wiring and plumbing applications, and aluminium, often used in window frames. In the latter case, it is worth mentioning that it is possible to recycle the material into new window profiles, provided that paint finishes are avoided. It is estimated that 92%–98% of aluminium in EU buildings is already collected for recycling (Boin and van Houwelingen, 2004).

3.4. Reuse in the construction sector – A quantitative overview

While recycling is already employed as a way of handling several construction and demolition waste streams, reuse is not yet implemented in a significant manner at the European level: it is estimated that <1% of CDW materials are effectively reused (Deweerdt and Mertens, 2020). Though quantitative data on reuse are largely unavailable, reuse potential values, as found in literature, are collected in Table 4. Details about which data points are obtained from each of the 23 sources and what elaborations have been carried out in this paper are available in the supplementary information (*Reuse* tab). Reuse potential is defined in Iacovidou and Purnell (2016) as "a measure of the ability of a construction component to retain its functionality after the end of its primary life". It should be noted, however, that these reuse potential rates do not necessarily include the implementation of DfD measures. Based on the collected values, it appears evident that there are large variations across literary sources, in terms of estimated reuse potential. This is partially to be attributed to the different approaches used in the calculations, and partially to the significant uncertainties connected to reuse capacity.

While reuse potential is a measure of the level of reuse which could be achieved under the right circumstances, actual reuse across Europe appears to be rather limited. Values found in literature often cover only specific countries and years, thus making it difficult to extrapolate information at a larger (European) scale. The materials which are currently being reused, even if in small measure, are bricks, steel, aluminium, and timber. The available country-level information, obtained from 13 sources, has been collected in Table 5. Additional details about these studies are available in the supplementary information.

The available data, however fragmented, shows considerable gaps between the current situation and the achievable reuse level for several materials, highlighting the potential for significant improvements. Implementing the measures described in this paper (i.e., selective demolition and DfD) at a large scale and across different countries is one of the routes that would make it possible to bring up the European reuse levels, leading to increased circularity within the construction sector.

3.5. Perspectives for life cycle assessment

The present study reviews the techno-scientific literature to provide an overview of the improvement potentials associated with selective demolition and design for deconstruction relative to what is mainly the current practice. Building upon previous studies, this work advances

Table 4
Reuse potential for different building materials and components. Different values for the same component are derived from different sources. PVC: polyvinyl chloride.

Material	Components	Reuse potential (%)	Sources
Bricks	Bricks bonded with cement mortar	0	Thormark (2000), Gorgolewski and Ergun (2013), Iacovidou and Purnell (2016)
	Bricks bonded with lime mortar	>50	Thormark (2000), Gorgolewski and Ergun (2013), Iacovidou and Purnell (2016)
	Bricks (generic)	10; 50; 57	Institute for Local Self-Reliance (2006), Hopkinson et al. (2018), Douguet and Wagner (2021), Kancheva and Zaharieva (2023)
Timber	Structural timber	25; 39; >50; 59	Thormark (2000), Institute for Local Self-Reliance (2006), Gorgolewski and Ergun (2013), Iacovidou and Purnell (2016), Höglmeier et al. (2017)
	Flooring	~50; >50; 64-85	Sassi (2002), Gorgolewski and Ergun (2013), Iacovidou and Purnell (2016)
	Roof trusses	<50	Earle et al. (2014), Iacovidou and Purnell (2016)
	Solid wood door	~50	Gorgolewski and Ergun (2013)
	Window frame	<50	Gorgolewski and Ergun (2013)
Concrete	Concrete (generic)	13%	Cristóbal et al. (2024)
	Structural concrete	0; <50	Gorgolewski and Ergun (2013), Iacovidou and Purnell (2016)
	Staircases and stair units	<50	Iacovidou and Purnell (2016)
	Precast concrete	~50	Iacovidou and Purnell (2016)
	Concrete panels	80-85	Huuhka et al. (2019)
	Roof tiles	>50	Iacovidou and Purnell (2016)
Steel	Structural steel	>50; 79	Cooper and Allwood (2012), Iacovidou and Purnell (2016)
	Hot rolled steel	80	Cooper and Allwood (2012)
	Fabricated steel plate	10	Cooper and Allwood (2012)
	Steel connections	0	Cooper and Allwood (2012), Iacovidou and Purnell (2016)
	Reinforcing steel	0; 4; <50	Cooper and Allwood (2012), Iacovidou and Purnell (2016)
	Steel sheet	47	Cooper and Allwood (2012)
	Cold formed section	50	Cooper and Allwood (2012), Iacovidou and Purnell (2016)
	Cladding	50	Cooper and Allwood (2012), Iacovidou and Purnell (2016)
	Steel in buildings	38	Cooper and Allwood (2012)
	Steel in construction	29	Cooper and Allwood (2012)
PVC	Pipe	0	Iacovidou and Purnell (2016)
	Roofing sheet	0	Iacovidou and Purnell (2016)
	Window frame	0	Iacovidou and Purnell (2016)
Aluminium	Window frame	0; 50	Cooper and Allwood (2012), Iacovidou and Purnell (2016)
	Cladding	50	Cooper and Allwood (2012)
	Aluminium in construction	50	Cooper and Allwood (2012)
Ceramic	Roof tiles	>50	Iacovidou and Purnell (2016)
	Floor tiles	2	Sassi (2002)
	Ceramic and tiles	10	Cristóbal et al. (2024)
Copper	Pipe	0	Iacovidou and Purnell (2016)
Insulation	Mineral wool	0; <50	Thormark (2000), Gorgolewski and Ergun (2013), Iacovidou and Purnell (2016), WOOL2LOOP (2022)
	Stone wool	0	NFDC (2013)
	Façade insulation	19	Hartwell et al. (2021)
Gypsum plasterboard	Finish	0; <50	Thormark (2000), Gorgolewski and Ergun (2013), Iacovidou and Purnell (2016), Sandin et al. (2021), Klinge et al. (2022)
Glass	Window pane	20; 33; <50	Hardie (2011), Monier et al. (2011)

and systematises the knowledge available to date by distinguishing between building structural typologies (concrete, masonry, timber, and steel) and by looking at the consequences of selective demolition and DfD at the specific material and building component level, whenever possible. Such a systematic and comprehensive analysis of the measures available provides a useful tool for the users to link such measures to their expected effects in terms of building material circularity and waste management options.

Future work should focus on providing a detailed quantification of the environmental and socio-economic benefits associated with the solutions discussed here, and can benefit from starting from the comprehensive analysis of measures herein collected. The quantification of environmental and economic benefits requires careful attention being paid to the assessment methodology, notably in terms of functional unit and system boundary, to capture the actual effects of these solutions. Indeed, it is important to distinguish between an assessment that focuses on the building services (e.g. functional unit being square metres of floor area for well-determined functions) and on the valorisation of the material or component at the end-of-life (e.g. managing a component or material flow at EoL). In the first case, it is clear that systems with and without DfD measures have to be compared across all the life cycle

Table 5
Material reuse rates.

Material	Reuse rate (%)	Country and year	Sources
Bricks	6	UK (1998)	WRAP (2008)
	10	UK (2007)	Kay et al. (2012)
	3	DK (2016)	Hardie (2011), Santoro (2020), Cristóbal et al. (2024)
Timber	30	UK (1998)	ARUP (2021)
	1.89	Flanders (2005)	Monier et al. (2011)
Steel	5	UK (2012)	Rakhshan et al. (2020)
	14	NL, SE, UK (2000-2001)	Sansom and Meijer (2002), Durmisevic and Noort (2003)
	12	AUS (2011)	Hardie (2011)
	10	EU (2020)	Cristóbal et al. (2024)
Aluminium	5.5	AUS (2011)	Hardie (2011)
	10	EU (2020)	Cristóbal et al. (2024)

stages, i.e. using the same system boundaries. In the second case, the system boundaries differ; the boundary of the (waste) system with DfD has to be expanded to account for all the DfD-related changes that have affected the material or component flow before its EoL. In contrast, for the (waste) system without DfD the boundary can be limited to the end-of-life only. It is clear that such an assessment can be performed only if the waste flows in the two cases have comparable properties (while being designed and produced differently in their upstream supply chain stages), i.e. if the functional unit is the same. Another relevant issue is that of allocation, as already mentioned in sections 1.1.1 and 1.1.2. The ISO 14,044 standard recommends that allocation be avoided whenever possible (International Standards Organisation, 2006), by way of either process subdivision or system expansion. However, allocation is particularly useful when assessing impacts over multiple life cycles, as it provides a pathway to assigning environmental burdens and benefits to the different cycles while avoiding double counting. Nevertheless, there is no consensus on which allocation approach is the most suitable, and the standard itself provides several options. It might therefore be necessary to make an appropriate choice on a case-by-case basis. Other challenges, already mentioned in section 1.1.3, include the uncertainties associated with the long lifespan of buildings, namely the unpredictability of user behaviour, as well as changes in energy requirements and construction techniques and materials. All these factors complicate not only the implementation of DfD solutions, but also the accurate assessment of their impacts.

An EU-level life cycle assessment of the possible environmental benefits connected with reuse has been conducted as part of the previously mentioned 2023 JRC report (Cristóbal et al., 2024). While the assessment does not focus on the environmental consequences of an increased DfD implementation, it does include the increased consumption associated with selective demolition in its estimation of the potential benefits of reuse. The study highlights the advantages of reuse as compared to other EoL treatment options (recycling, incineration, landfilling) for the management of one tonne of material, covering the stages from waste generation to processing including, when applicable, the credits from avoiding material extraction and production. The results are shown in Fig. 3: negative values indicate that reuse is a better option, in terms of GHG emissions (C-footprint), than the waste treatment to which it is being compared, while the opposite is true for positive values. These results show that increased reuse would have a beneficial effect in the management of most materials. The additional GHG savings from reuse span from 1.30 kg CO_2 for gypsum to 5464 kg CO_2 for EPS, per tonne of material managed. Note that for the case of timber reuse incurs less savings than incineration or recycling, but the authors (Caro et al., 2024; Cristóbal et al., 2024) clearly explain that this occurs because of methodological issues related to the fact that cascading cycles, biogenic carbon storage and indirect land use change effects were not accounted for (when included, reuse would outperform the remaining). For bricks, reuse appears less beneficial than recycling to cementitious materials, but the authors stress that significant uncertainties are associated with such recycling pathways and its expected benefits of truly replacing cement.

3.6. Policy implications

The current EU legislation on CDW management is mainly driven by recovery targets enforced in the EU Waste Framework Directive (70% CDW recovery target by 2020), which are already fulfilled by many countries (European Parliament and Council, 2008). However, it is known that such recovery targets are reached via recovery operations producing mainly recycled aggregates from the heavy fraction of CDW (via crushing and simple selection processes), ultimately turning waste into low quality aggregates for environmental reclamation (filling) and road base material, substituting for natural aggregates in the best case. The environmental benefits of such recovery pathways are proved to be limited: considering building-related CDW and excluding excavated soil and dredging spoils, moving towards best-available recycling processes can save up to 264 kg CO_2-eq. t^{-1} CDW, which would incur 33 Mt CO_2-eq. additional annual savings relative to the *status quo* management characterised by a mix of recycling, landfill and incineration (Caro et al., 2024). Further fostering reuse, to the extent technically possible, can incur up to ca. 48 Mt CO_2-eq. additional annual savings relative to the *status quo* management (Cristóbal et al., 2024). This suggests that, while current waste policy and related recovery target is certainly achieving a diversion of CDW from landfills, its actual effect on environment and on reducing primary material demand for our economy, particularly in the construction sector, is limited and ample margin for improvement exists.

Having in mind that the spirit of the new CEAP is precisely that of turning waste into resources by producing secondary material that can displace and reduce the demand for primary material, the current work serves as a basis to illustrate the consequences that an effective implementation of selective demolition and design for deconstruction can have on the circularity of the materials in the construction sector. The study clearly highlights where and how reuse (or even repurposing) options can be employed and where and how the quality of recycling and recycled materials thus produced can be improved. This is a building block towards promoting innovative solutions that aim to the highest level of the waste management hierarchy, prioritising reuse and quality recycling over recovery operations that mainly achieve diversion from landfill.

According to Röck et al. (2021), the EU policy objectives related to the building sector concern improvements to energy efficiency, increases in renewable energy use, circularity and low-carbon material uptake, climate change adaptation and resilience and monitoring of environmental performance. Several legislative pushes have been made with the aim of reducing energy consumption during the use phase of a building. The EU has moved towards achieving energy-related goals, impacts related to the other phases of a building's life cycle have become prominent. It is in this context that increasing circularity and reducing waste production grows relevant. However, the lack of a shared definition of what DfD entails, and of legislation clearly addressing the related measures, has been identified as a barrier to the implementation of DfD (Kanters, 2018; Giorgi et al., 2022), highlighting a policy gap to be filled. This study, in showcasing available DfD and selective demolition measures, hopes to contribute to setting a solid basis on which such policy might be built.

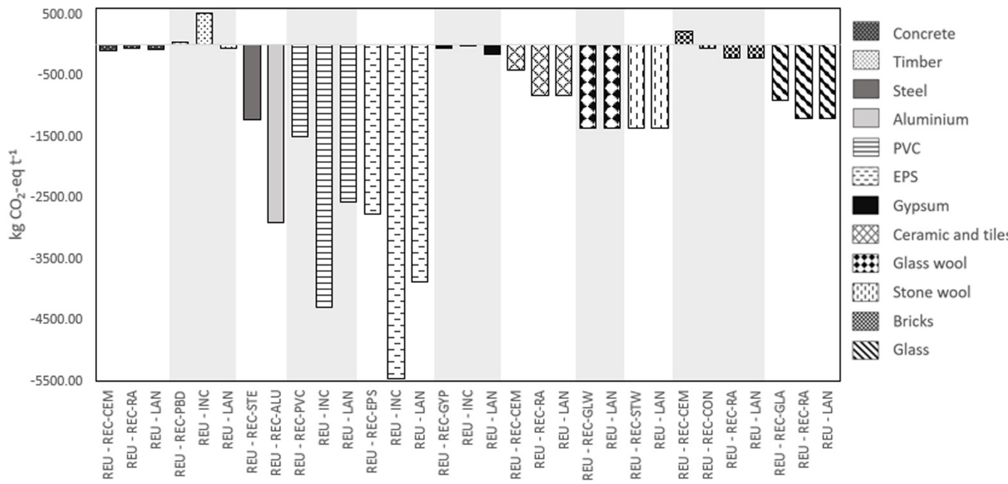

Fig. 3. GHG emission savings per tonne of individual material managed, calculated as the net difference between the C-footprint of reuse and alternative EoL options (based on data from Cristóbal et al. (2024)). REU: preparation for reuse; REC: recycling; INC: incineration; LAN: landfill. Recycling is differentiated on the basis of the product resulting from the recycling process: cementitious material (CEM), recycled aggregate (RA), particleboard (PBD), iron scrap (STE), aluminium (ALU), PVC, EPS, plasterboard (GYP), glass wool fibres (GLW), stone wool fibres (STW), concrete (CON), flat glass (GLA). The results for timber reuse assume only one cascading cycle and no benefits from carbon biogenic or avoided land-use-change effects.

4. Conclusions

The EU has developed a comprehensive body of legislation aimed at promoting circularity across all sectors of the economy; among these, the building sector occupies a prominent role, due to its considerable environmental impacts. While prevention of waste remains an obvious priority, higher quality recycling and reuse of building materials and elements are key to foster circularity in the sector. This study takes an in-depth look at different approaches aimed at promoting high-quality recycling and reuse, namely selective demolition and design for deconstruction, and assesses their potential for implementation, developing a taxonomy which covers different building types and levels of granularity (from the material to the component level). In doing so, it highlights the broad range of possible applications of these measures, sets the basis for future studies aimed at quantifying the environmental benefits connected to their implementation, and provides a support for the development of policies intending to promote circularity.

CRediT authorship contribution statement

Giulia Pristerà: Investigation, Methodology, Visualization, Writing – original draft. **Davide Tonini:** Conceptualization, Methodology, Writing – review & editing, Supervision, Project Administration. **Marco Lamperti Tornaghi:** Methodology, Writing – review & editing. **Dario Caro:** Resources, Data curation. **Serenella Sala:** Conceptualization, Writing – review & editing, Supervision.

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

The underpinning data used in the study are available in the supplementary material.

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Appendix A. Glossary

A glossary of terms used throughout the text is provided below.

- *Backfilling*: Backfilling is defined in the EU as "a recovery operation where suitable waste is used for reclamation purposes in excavated areas or for engineering purposes in landscaping and where the waste is a substitute for non-waste materials" (Eurostat, 2023a).
- *Conventional demolition*: Demolition, or conventional demolition, can be defined as the "dismantling, razing, destroying or wracking any building or structure or any part thereof by pre-planned and controlled manner" (Pranav et al., 2015).
- *Design for deconstruction*: There is no internationally agreed upon definition of design for deconstruction (Kanters, 2018). The term is used to indicate measures implemented from the design stage and aimed at facilitating the non-destructive disassembly of a building at its end of life, with the goal of increasing the reuse and recycling potential of select building elements. In the present work, the terminology design for deconstruction is used as an umbrella term for not only design for deconstruction itself, but also design for adaptability, design for disassembly, and reversible building design.
- *Recycling*: according to the EU Waste Framework Directive, recycling can be defined as "any recovery operation by which waste materials are reprocessed into products, materials or substances whether for the original or other purposes". This definition does not include energy recovery operations, nor does it include materials used for backfilling purposes (International Standards Organisation, 2006; Pranav et al., 2015).

- *Preparation for reuse*: Preparation for reuse includes all those recovery operations (checking, cleaning, repairing) through which "products or components of products that have become waste are prepared so that they can be re-used without any other pre-processing" (Eurostat, 2023b).
- *Recovery*: Waste recovery includes all those operations "the principal result of which is waste serving a useful purpose by replacing other materials which would otherwise have been used to fulfil a particular function, or waste being prepared to fulfil that function, in the plant or in the wider economy" (Eurostat, 2023c).
- *Reuse*: Reuse of waste refers to "any operation by which products or components that are not waste are used again for the same purpose for which they were conceived" (Eurostat, 2023d).
- *Selective demolition*: Selective demolition is defined as the "removal of materials from a demolition site in a predefined sequence in order to maximise recovery and recycling performance" (European Commission, 2018b).

Appendix B. Research data statement

Supplementary material related to this article can be found online at https://doi.org/10.1016/j.resenv.2024.100153.The underpinning data used in the study are available in the supplementary material.

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