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Environmental impacts of Design for Reuse practices in the building sector

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ABSTRACT

Actors of the construction sector are facing the challenge of reducing their carbon footprint and ideally reaching carbon neutrality. Reuse of structural elements made of concrete is of particular interest, given the large use of this material worldwide and its high environmental impact. Reusing constructive concrete elements is however challenging, particularly because connections between concrete structural elements are difficult to disassemble. It is then worth designing reuse techniques for concrete load-bearing elements and to verify their environmental performance using comprehensive methods such as Life Cycle Assessment. Based on the Design for Reuse concept, this article assesses the environmental impacts of a reusable structural portal frame constitutive of a concrete building and compares it to a traditional design with new materials. It relies on data collected through an experimental protocol of reinforced concrete structures construction/deconstruction/reconstruction using hydrodemolition. Impact scores are significantly reduced for all environmental categories after a first reuse cycle, both at the scale of a portal frame or a building. Concrete, and particularly high performance concrete, has durability qualities allowing to undergo several usage cycles. The effectiveness of environmental benefits however depends on functional downgrading and material losses. Guidance should then be provided to insure that future reuse practices will actually provide the expected benefits. This has to be conducted in parallel to full-scale experiments of load-bearing elements disassembly to estimate the realistic rates that can be obtained when deconstructing a building.

Keywords:

Design for Reuse

Buildings

Concrete structures

Life cycle assessment

Deconstruction

Circular economy

1. Introduction

1.1 Reuse as a strategy to improve the environmental performance of buildings

In its 2021 Global Status Report for Buildings and Construction, the United Nations Environment Program (UNEP 2021) points to the alarming situation of the building sector at the international level. With CO₂ emissions estimated at 11,7 GT in 2020, the building sector is a major contributor to climate change, causing up to 36% of the total CO₂ emissions worldwide. With the current pace of population and economic growth, CO₂ emissions are expected to keep growing if no solution to reduce the carbon footprint of buildings and constructions is implemented. The building sector also contributes to other environmental burdens (Brütting et al 2019), such as resource depletion (UNEP 2019), energy consumption and waste generation (Ibrahim 2016; European Commission 2020).

Improving the environmental performances of buildings could help mitigating the global impacts of societies on climate change (Hoxha et al 2016). With current practices, 5 to 12% of the greenhouse gases (GHG) emitted during the life cycle of a building are released during the extraction of raw materials, the fabrication of construction products, the construction, renovation and demolitions processes (European Commission 2020), representing the embodied GHG emissions (Röck et al 2020). The share of operational GHG emissions, occurring during the use stage of the building, is however expected to decrease with the reinforcement of energy efficiency standards. The share of materials in the global carbon footprint of a building is in turn likely to increase. While a major lever of change is related to the improvement of the energy performance of buildings during their use stage (Blengini et al 2010), adopting circular actions in the building sector could also decrease the embodied

GHG emissions (EEA 2016). The recirculation of materials, particularly reuse, are among the practices considered to reach this goal (Koutamanis et al 2018).

Reuse is considered a way to improve the environmental performances of buildings, as it avoids the generation of construction and demolition (C&D) waste and substitutes primary materials and products, with potential benefits in terms of GHG emissions reduction and energy efficiency (Cai and Waldmann 2019). Unlike recycling which consists of reprocessing wastes to produce new materials, reuse preserves the function of the reused material or component after its reconditioning (Iacovidou and Purnell 2016, Brütting et al 2018). Parallel to its expected environmental benefits, a generalized reuse strategy might have important economic repercussions given the volume of C&D waste currently generated (Nußholz et al 2020).

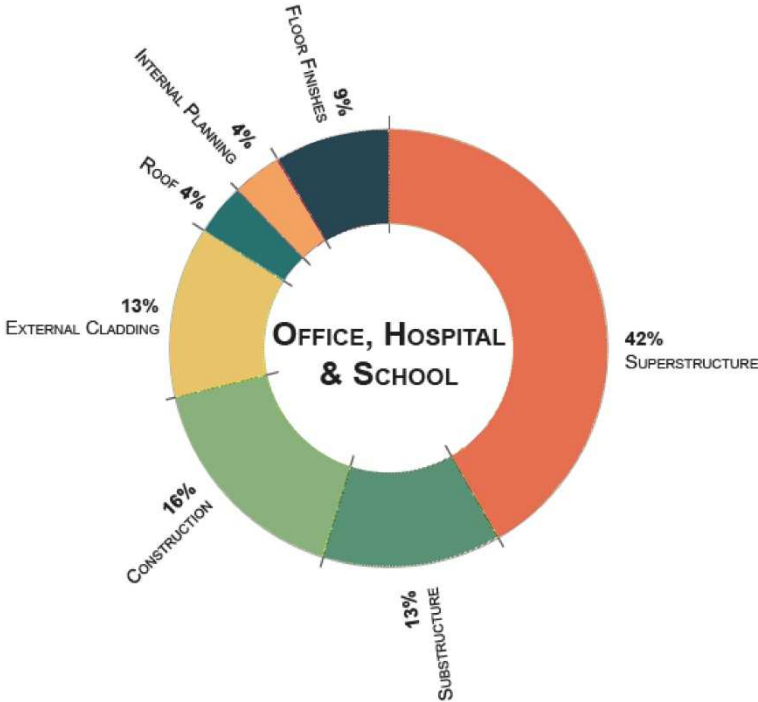


Fig. 1. Average breakdown of embodied energy for building elements, based on Qarout (2017) and Kaethner and Burrige (2012).

Among constructive elements (Figure 1), load-bearing systems require material- and energy-intensive manufacturing processes (Brütting et al 2018). They contribute to the largest share of embodied energy (Lankhorst et al 2019, Cavalliere et al 2018), estimated at about 40% for buildings of average or low energy performance (Marzouk et al 2017). They also account for at least 50% of the embodied carbon of a building (Kaethner and Burrige 2012; Veselka et al. 2019). Reuse of load-bearing elements is then considered a promising way to improve the environmental performances of buildings (Fivet 2019), especially when implemented over several life cycles.

Structural elements made of concrete are of particular interest. In France, 80% of the built heritage is made of concrete (IFSTTAR 2018). Concrete is also the most used building material worldwide (Naik 2008). Reusing constructive elements made of concrete is however challenging, particularly because connections between concrete structural elements are monolithic and difficult to disassemble (Xiao et al 2017). Given the high environmental impact of this material, it is worth designing reuse technics for concrete load-bearing elements and to verify their environmental performance using comprehensive methods such as LCA.

1.2 Design for Reuse (DfReu): a framework for reuse practices in the building sector

To generalize the practices of reuse in the building sector, a framework must be proposed to its actors. Design for Deconstruction or Design for Disassembly (DfD) is an

existing concept (Akadiri et al 2012) offering to integrate deconstruction in the design of buildings to increase the recovery of materials and structural components at the end of life (EoL) of a construction, thus reducing demolition waste (Crowther 2001; Durmisevic and Yeang 2009). DfD generally focuses on the EoL of structures or buildings and usually fails at providing guidelines on the integration of recovered materials and constructive elements in a new (or retrofitted) structure. DfD encourages valorization through recycling or energy recovery. Some studies have however tested the performance of DfD components in a new structure (Xiao et al 2017).

Given the limitation of DfD, we propose to adapt the concept of Design for Reuse (DfReu), introduced by Gorgolewski (2018) and Iacouvidou and Purnell (2016), as the framework focusing on the design for the reuse of structural elements (Bertin et al 2020). In the original definition, DfReu is understood as the way to incorporate recovered components in the design of a new building or structure (Iacouvidou and Purnell 2016), thus focusing on the sole design and construction stages of the building. In our definition, we consider that DfReu, in addition to reflecting on the conditions for which reuse of construction components is maximized, shall consider the way such components are dismantled, both prior to the construction of the new structure, and as an anticipation of deconstruction, similarly to DfD.

To respond to the practical application of DfReu, Bertin et al (2020) addressed complementary means to reach the objectives of structural component cycling such as the implementation of reinforced traceability and the establishment of a materials bank. DfReu also relies on anticipating changes in the use of materials and constructive elements. To that end, we draw on the concept of reversible building, applied to both office and residential programming. The underlying principle is to design a structural grid to be flexible enough to accommodate different functions throughout its life cycle(s) in order to reduce buildings obsolescence related to use changes. Moreover, DfReu implies the existence of a stock of construction elements ready for reuse. To that end, the proposed approach considers two ways to proceed: “with a stock” or “from a stock”. A “design from a stock” leads to 100% of elements reused, using only elements from the stock. A “design with a stock” seeks to integrate as many reused elements available in the stock as possible, completed with others and new elements. At the end of life, the DfReu concept considers the disassembly of the elements and the reconstitution of a stock available for a future building.

1.3 Assessing the environmental relevance of DfReu using LCA

The expected environmental benefits of DfReu, namely mitigation of GHG emissions, of natural resources depletion and reduction of waste generation, are however to be demonstrated. Applying DfReu's principles for designing reusable buildings can indeed lead to a slight oversize of load-bearing structures compared to a conventional building, and consequently be more impactful than traditional practices, particularly in terms of energy and resources consumption. It is therefore necessary to conduct a comprehensive assessment of DfReu applications, considering the possible trade-offs from an environmental issue to another, and including the multiple life cycles of a structural component.

Life Cycle Assessment (LCA) is a powerful method increasingly used to comprehensively quantify the environmental impacts of circular and reuse practices in the construction sector, at the component (Buyle et al 2019; Eberhardt et al 2019b) or building level (Rasmussen et al 2019; Eberhardt et al 2019a). LCA has been applied since the 1990s to the construction sector and particularly to evaluate buildings (Peuportier et al 1997; Cabeza et al 2014). It has been particularly used for the assessment of construction and demolition waste scenarios (Blengini 2009; Butera 2015; Mastrucci et al 2017). Assessment of circular practices and particularly reuse is still at an early stage (Palacios-Munoz et al 2019; Densley Tingley and Davison 2012). Early studies on concrete structures have however shown the interest of reuse (Xia et al 2020).

Several limitations of LCA are reported in the literature, particularly when related to the assessment of reuse and “circular” practices, with still research gaps when addressing end-of-life modelling (Sandin et al 2014) and allocation aspects (Reap et al 2008; Schrijvers et al 2016). The availability of adequate data is also a recurring issue (Nizam et al 2018). Najjar et

al (2017) have identified gaps in the databases and pointed out the inadequate data inventory in the early design phases. This lack of data reduces the potential for LCA application. As a result, some studies rely on simplified assumptions (Yung and Wang 2014). The average values and simplified hypothesis may disregard the differences between reuse and new construction practices. Inaccuracy in data collection can be detrimental to the assessment of reuse impacts, especially for the construction stage (building and rebuilding). Therefore, it is essential to have foreground data to properly model the reuse processes.

Objective of the article

The overall goal is to evaluate the environmental opportunity of reusing load-bearing systems made of concrete. This article assesses the environmental impacts of a reusable structural portal frame constitutive of a concrete building using LCA and compares it to a traditional design with new materials. It relies on data collected through an experimental protocol of reinforced concrete structure construction/deconstruction/reconstruction.

The paper is organized as follows: in section 2, the method adopted for the study is explained. It consists of first designing structural applications of DfReu, tested through an experimental protocol on portal frames and second verifying the environmental performances of such applications using LCA. The results of the concrete portal frames LCA are presented in section 3, at two scales: first at the scale of the portal frames; second at the building scale. In section 4, the results of the environmental assessment are discussed. Finally, section 5 provides some practical recommendations to the actors of the construction field and section 6 concludes the article.

2. Methodological framework

When optimizing reusable structures, the logic of engineers is to make assemblies between elements (beams vs. columns) in the form of hinged connections, deemed to be easier to dismantle. This solution has however two disadvantages. First, hinged connections are generally very expensive because they require steel elements of complex shape, and, second, they require the creation of additional specific bracing which is also expensive. The authors point of view is rather to consider braced multi-storey buildings with rigid assemblies, i.e. embedding between beams and columns, which constitutes simpler systems. The rigid assemblies allow the building to support wind loads without any bracing elements.

Based on this assumption, we first focused on the assessment of mechanical behavior of reinforced concrete portal frames. We explored the behavior of new and reused portal frames using an experimental protocol. Parameters are concrete strength and steel overlapping. Among the many means of disassembly, we decided to use hydrodemolition. More details are given further on this technique. Based on these experiments, foreground data on processes were generated for LCA. After this step, we extrapolated results on a building scale.

2.1. Design for reuse (DfReu) applied to a reinforced concrete portal frame

Four reusable concrete portal frames integrating different connection principles have been manufactured for testing (Bertin 2020). The tested portal frames are supposed to be included in a building where the columns are continuous. The removable assembly area (keying area or keyway, Figure 2 and schematized in grey in Figure 3) was then located at the ends of the beams. The continuous column is a choice allowing an application to multi-storey building structures. The reinforcement is designed in such a way that the beam and the column can be dissociated once the keying concrete is hydrodemolished. It is a particular sequence of reinforcement assembly that allows a reversible independence of the different elements. This technique would also be applicable in the case where the columns are not continuous. In that case, it would be necessary to design the continuity of the columns reinforcement in an appropriate way in order to satisfy the same disassembly principle.

The size of the tested prototypes was set at a 1/3 scale in order to comply with the laboratory equipments. All four portal frames have variations in the keying area according to sketches in Figures 2 and 3. The reusable portal frames were structurally tested, then

deconstructed at the keying area by hydrodemolition and reconstructed through the reconstruction of the keying area. The reused portals frames were then tested again to verify their structural capacities before and after reuse.

Hydrodemolition consists here of using high-pressure water for localized concrete removal (Momber 2005). The water jet is controlled with great precision, which makes it possible to clearly define the area to be destroyed and to limit material losses. The experiment proved that all types of concrete can be hydrodemolished, normal and high performance concrete (HPC). It was chosen among different demolition processes because first it is a rapid method which does not create microcracks out of the demolished area; and second, steel rebars are not damaged during the process. The hydrodemolition causes a slight loss of concrete material at the level of the keying zone. The steel rebars, undamaged after the hydro-demolition process, are visible on Figure 2.

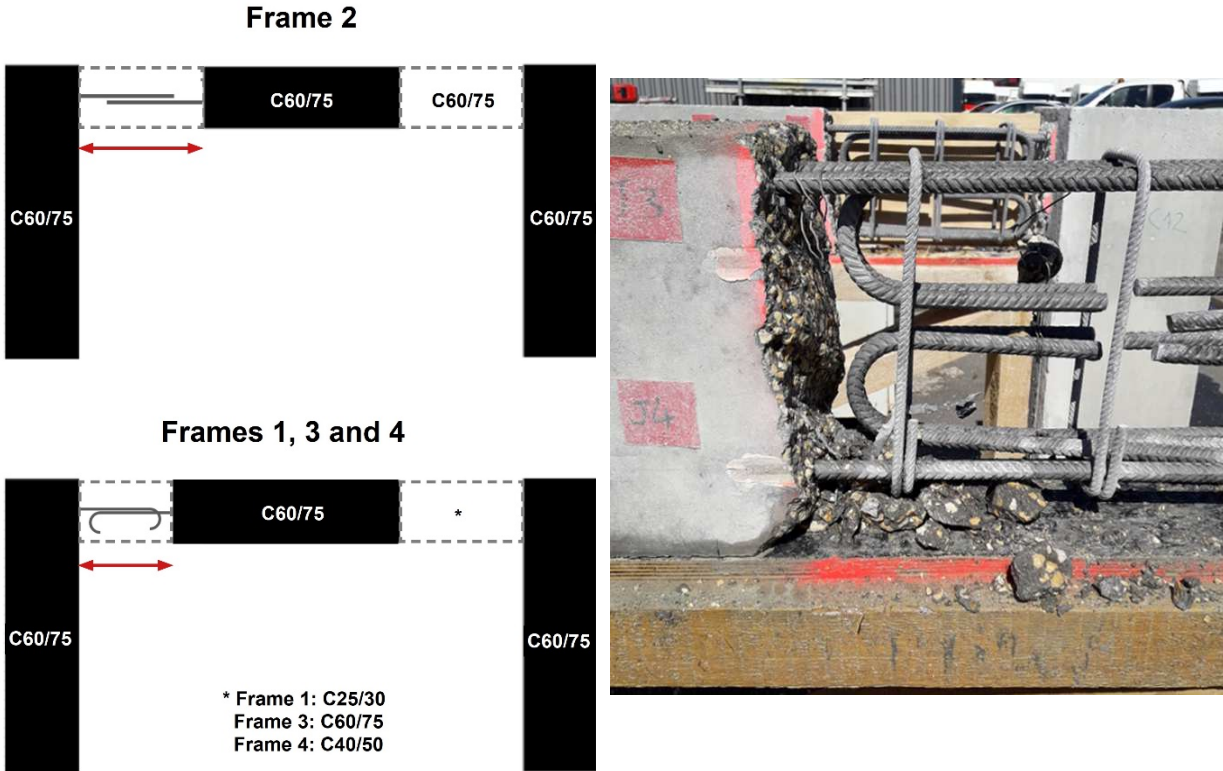


Fig. 2 Case study. Left: portal showing the rebars overlap depending on concrete strength (portal frame 2: strait overlapping, portal frames 1, 3 and 4: overlapping with cross ends) ; Right: result of the hydro-demolition process for the 1/3 scale portal frame.

The experimental protocol was set to verify whether a reused portal frame has the same structural behavior as the initial portal regarding Service Limit State (SLS). It has been concluded that the structure reconstructed after a first demolition had a similar behavior (SLS), which validates the proposed technic. This part of the experiment is not included in this paper, but is described in Bertin (2020). In order to adjust the load applied to the 1/3 scale portal frame, we considered a building designed as a superposition of portals, with a span of 6 meters. The bending moment at the keying area was calculated according to actions imposed in the Eurocode EN 1991-1 for offices. The same maximum bending moment in the specimen is reached for an external load of 73 kN.

The reusable portal frames allow to test different constructive systems addressing the same function and to verify the easy dismantling of the keying areas according to the concrete grade (strength). The reduction of the keying area length reduces the quantity of material to be hydrodemolished. The more the keying area is reduced, the more resistant concrete and reinforcing steel must be used (cross). Data on portals are given in table 1.

In anticipation of the LCA, all data on energy, raw material consumption, water, etc., have been recorded.

Table 1

Technical specifications and reference flows for each portal frame scenario.

	Reinforcement mass (kg)	Initial C60/75 concrete volume (m ³)	Rebars covering type	Keyway length (m)	Keyway concrete grade (MPa)	Keyway concrete volume (m ³)	Reuse concrete volume (m ³)
Portal frame 1	75,6	0,386	Cross	0.440	C25/30	0,054	0,386
Portal frame 2	73,9	0,378	Straight	0.506	C60/75	0,062	0,378
Portal frame 3	80,3	0,399	Cross	0.335	C60/75	0,041	0,399
Portal frame 4	80,7	0,396	Cross	0.360	C40/50	0,044	0,396
Non reusable portal frame	67,7	0,44	Cross	-	-	-	-

The differences between the reused portal frames relate to the nature of the concrete used in the connection and the type of rebars overlap (Table 1). They influence the length of the keying area to be hydrodemolished. The portal frames are made of C60/75 grade concrete (HPC), except for the keyway areas of portal frames 1 and 4, constituted of C25/30 and C40/50 normal grade concrete respectively. For each portal frame, the initial construction stage only involves primary material. Portal frame 1 then presents the keying area with the least resistant concrete associated with cross reinforcement to keep the keying length not too important. Portal frame 2 is constituted of HPC with straight reinforcement. Portal frame 3 is composed of HPC with cross reinforcement. This portal frame has the shortest keying length. Portal frame 4 has a strong keyway concrete but curved reinforcement. The structural behavior can be compared and verified regarding:

- the influence of the strength of the keyway concrete (portal frames 1, 3 and 4);
- the influence of the type of rebar covering type (portal frames 2 and 3).

Sequences of the experimental protocol are given in Figure 3:

- step 1: the dismantlable portal frames are manufactured
- step 2: the dismantlable portal frames are tested by simulating a normal office use
- step 3: the keying areas are deconstructed. The columns and beams can then be separated for reuse. The portal frames are then reassembled to simulate reuse.
- step 4: the reused portal frames are tested again. First, the same load is applied as in step 2 (office load) to see if there is a difference in behavior compared to the second step. Then a higher load is applied to reach the failure and to analyze the failure mode of the portal frames (purely structural interest). The reuse process simulated through the experimentation would occur in reality after several years/decades. Considering the fact that structural concrete housed in a building does not degrade, we assume a strong similarity between the experiment and reality.

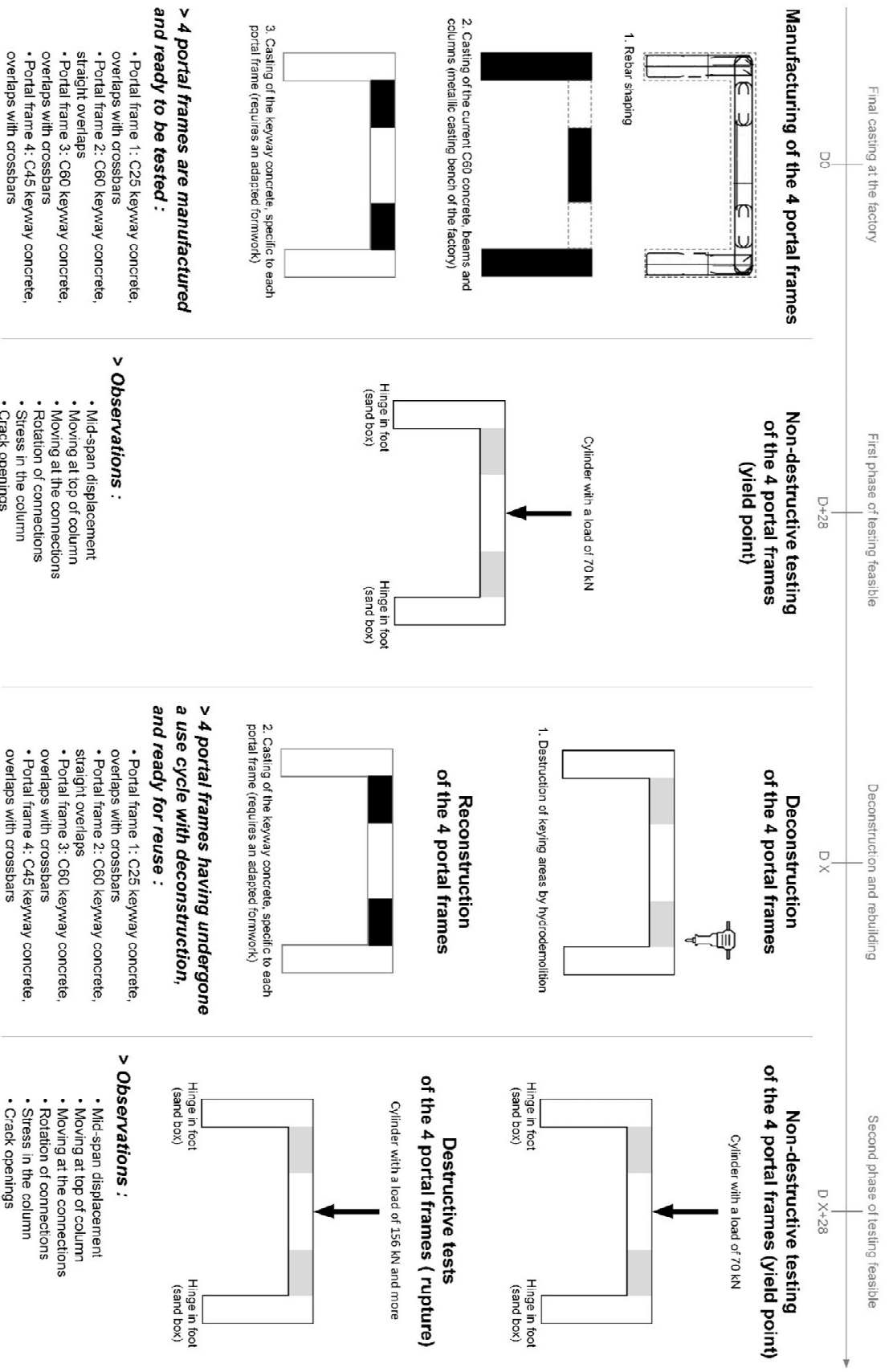


Fig. 3. Summary of the experimental protocol for the 4 portal frames.

2.2. LCA method

2.2.1 Goal and scope definition

LCA is applied to the 4 reinforced concrete portal frames on 1/3 scale, in order to evaluate the environmental performances of an anticipated reuse process (construction and deconstruction then reconstruction). Comparison is therefore sought:

- between the four reusable portal frames, to identify the design levers allowing to reduce their impact;
- between the group of reusable portal frames and a new portal frame more classically designed and qualified as "non-reusable", to identify the differences in the environmental impact of the processes, in particular deconstruction for reuse (vs. demolition for recycling).

According to expert knowledge, concrete material optimization in design generally involves the use of a more efficient concrete (high performance concrete HPC), which significantly reduces the total quantities used. In order to optimize the formwork for the realization of the portals, concrete sections are identical, but reinforcement was adapted according to the concrete strength and the type of overlapping – cross or strait (Table 1 and Figure 2).

The functional unit, on a scale of 1/3, is therefore defined as "a portal frame of 0.44 m³ of concrete (i.e. in dimensions (m): 0.35x0.35x1.4 for each of the columns, and 0.15x0.3x2.15 for the beam), with a span of 2.15 m, supporting a load of 73 kN, corresponding to an office use, for a life span of 50 years".

The different portal frames all meet the structural function corresponding to the same defined functional unit. The scenarios considered for LCA take into account the characteristics of the different assemblies (Table 1).

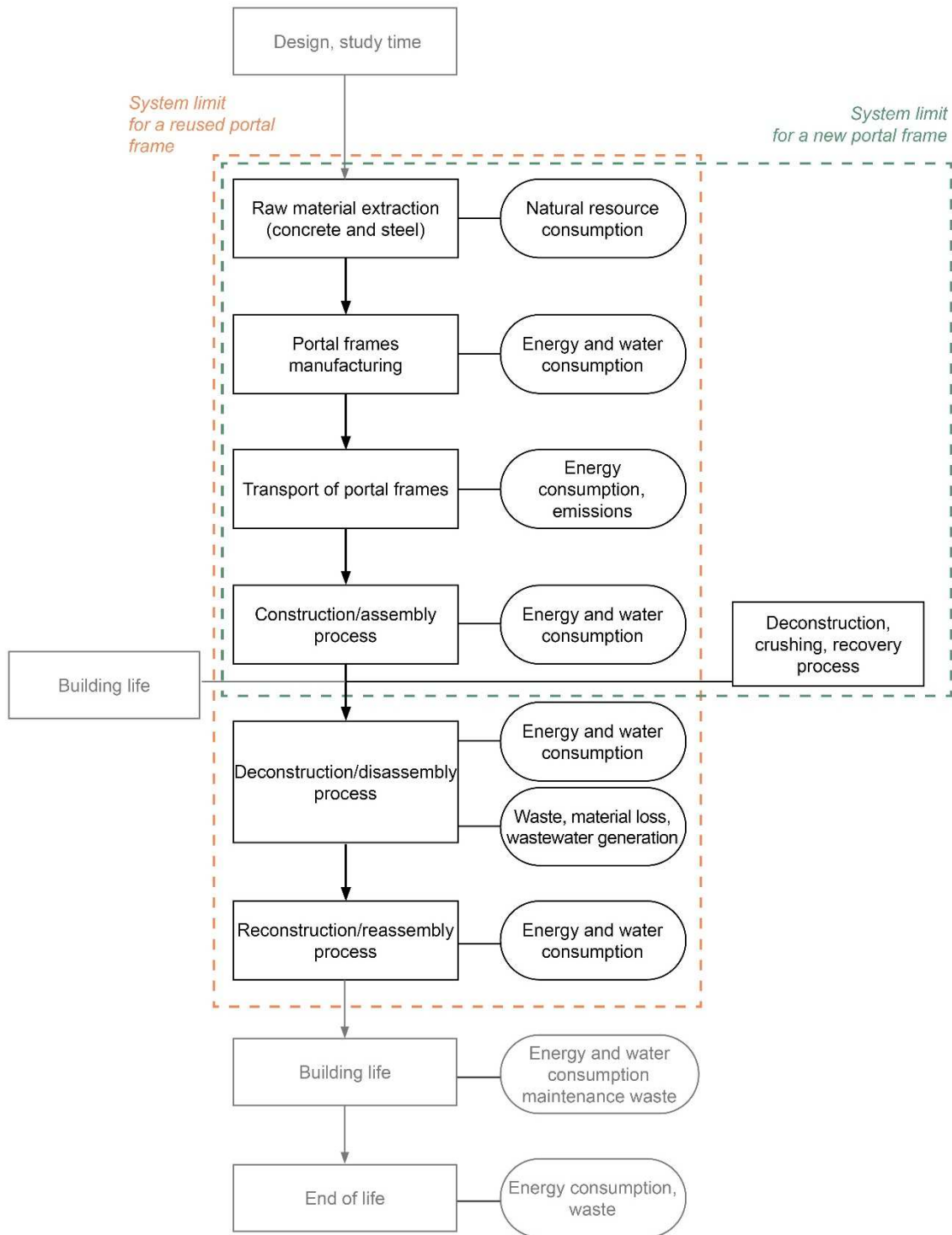


Fig. 4. System boundaries of the studied portal frame.

The system boundaries for each scenario (reference without reuse and reused portal frames) are given in Figure 4. The impact of the design stage, identical for all portal frames, is not considered. During the use stage - corresponding to the life cycle modules B1-B7 in the NF EN 15804+A1/CN standard (AFNOR 2014; AFNOR 2016) the structure, sheltered within the building (exposure class XC1 for concrete), does not deteriorate compared to the construction stage (module A5 of the same standard). The loss of material during hydrodemolition is verified to evaluate the impacts of the deconstruction process. In the portal frame LCA, we applied a cut-off allocation approach, considering that extraction and production of primary materials are attributed to the first cycle (Xia et al 2020).

2.2.2 Data collection

The reuse process tested through the portal experimentation is a prototype and has not yet been tested at full scale. A major part of the data was collected through the experimentation. To complete the inventory and model the system, data was further collected from structural engineers, construction companies and prefabrication plant employees. Collected data are the quantities of materials, energy (electricity, fuel), water and the different distances traveled at each stage of the manufacturing process (Figure 5 and Supplementary information). A depreciation for the facilities of the manufacturing sites have been considered. The different concrete mixes were adjusted using betonlab software (de Larrard & Sedran 1996)

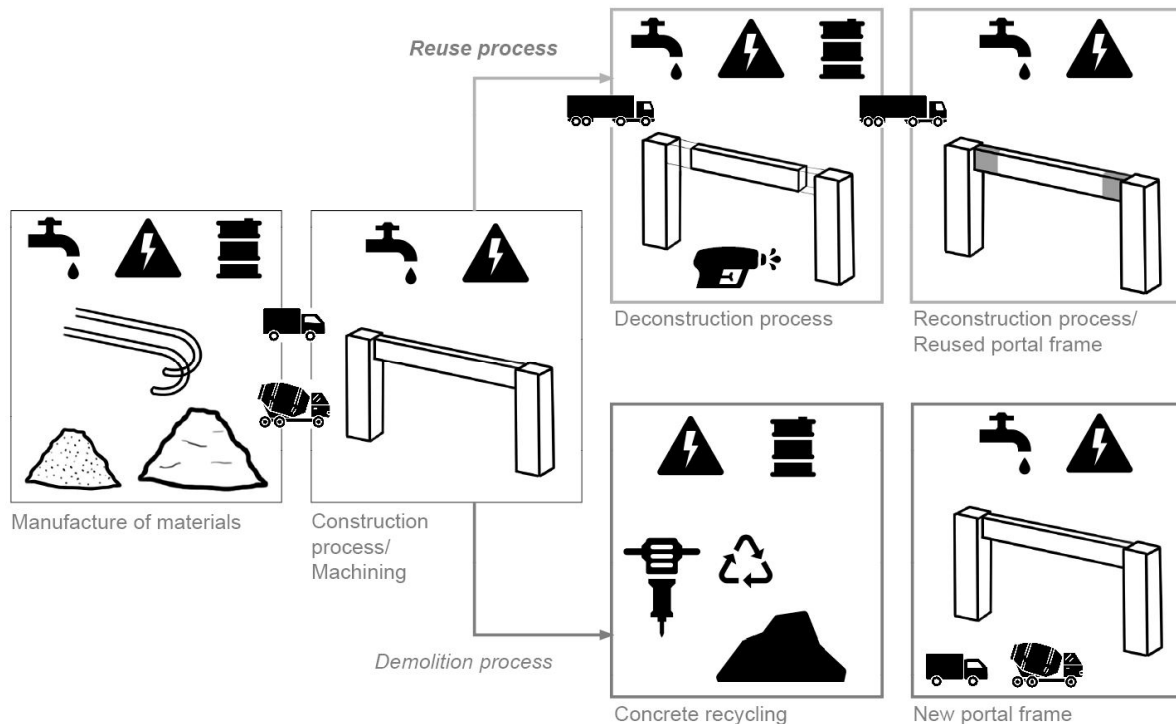


Fig. 5. Data collected during the construction and deconstruction processes.

2.2.3 Modeling assumptions

We considered the depreciation of the material installations for the manufacturing of the portal frames. The materials used for the first cycle are considered of primary production. In the prospective context of reuse, wood and concrete are considered recycled at the end of their life cycle (i.e. at the end of each use cycle for the "new" portal frame, and at the end of the ultimate cycle for the "reused" portal frame). Particularly for wood, we rely on the conclusions of research on post-consumer wood recycling (Privat 2019; Irle et al 2019) and cascading (Vis et al 2016; WWF 2021)[. For each use cycle, the reused portal frame will be compared to a new one, performing the same function.

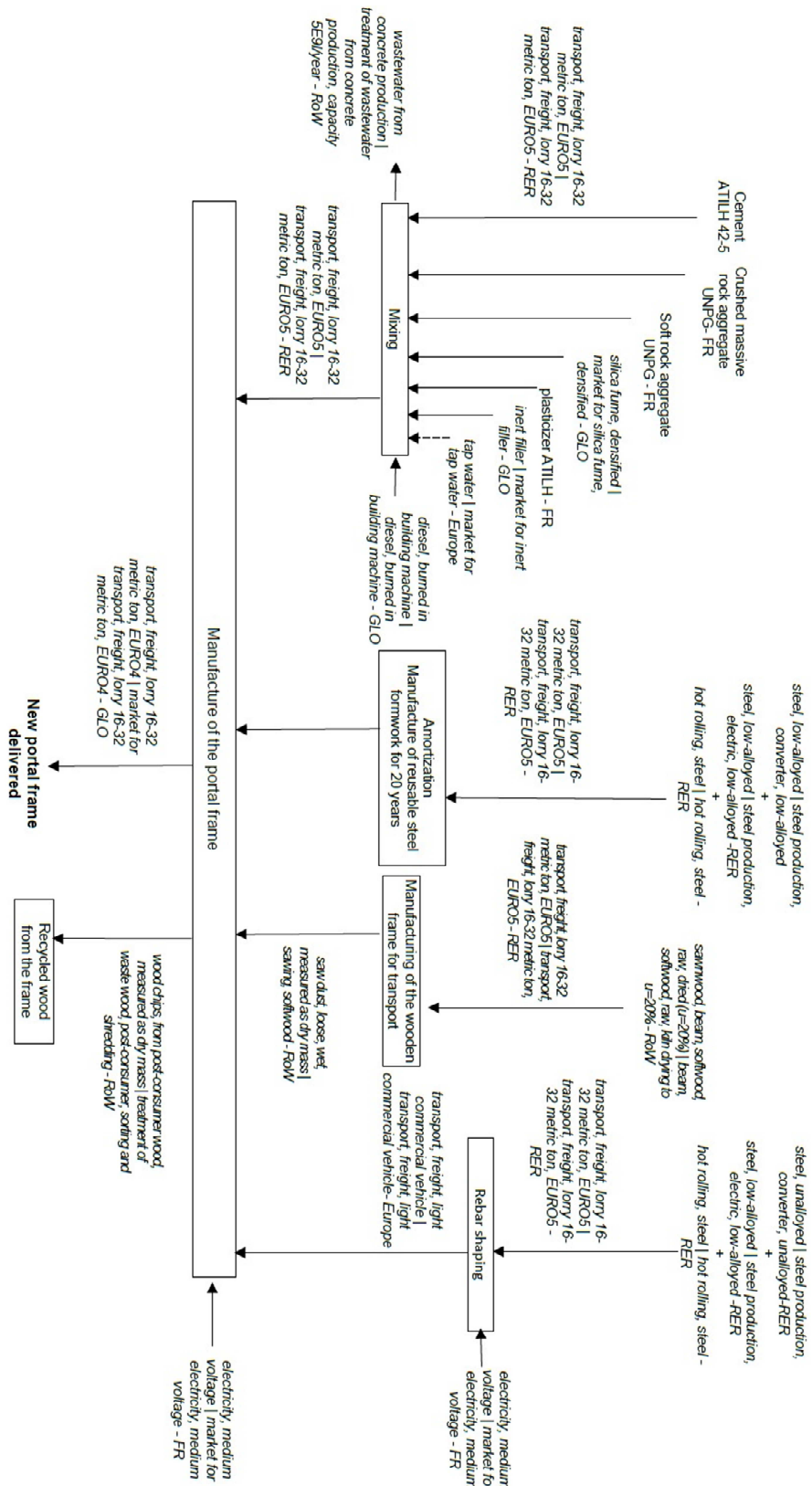


Fig. 6. LCA modeling for the manufacture of portal frame 1, initial use. Processes from theecoinvent data base are indicated in italic. The other processes were specifically created for the study, with the exception of the processes for cement and aggregates provided by French professional associations.

Figure 6 presents the flowchart of portal frame 1 up to its delivery for the first phase of testing, i.e. its actual first cycle of use. The flowcharts for portal frames 2, 3 and 4 are similar. In the same way, a model is developed for the second cycle of the portal frame, from its

deconstruction and rebuilding for delivery at the second test phase. In parallel, for each use cycle, a non-reusable portal frame (traditionally designed with new materials) is modeled and compared to the different variants of the reusable portal frames.

2.2.4 LCA software, LCI database and impact assessment method

To carry out the LCA, OpenLCA 1.8.0 software as well as Ecoinvent 3_2_cutoff database are used. The environmental assessment method considered corresponds to the set of indicators provided by the NF 15804+A1 (AFNOR 2014) standard and the complementary NF EN 15804/CN (AFNOR 2016) standard whose compatibility with OpenLCA has been established by Desbois (2017). The impact categories considered in this method are acidification of land and water, depletion of the ozone layer, eutrophication, photochemical ozone formation, air pollution, water pollution, climate change, abiotic resources depletion - fossil fuel resources, abiotic resource depletion – elements.

3. Results and Interpretation

3.1. Initial production of portal frames

Based on the experimental data, and using the new non-reusable portal frame as reference, Figure 7 shows the impact scores of the construction stage of each portal frame. Construction of the non-reusable portal frame appears to be less impacting than the construction of the reusable portal frames for 6 of the 9 considered environmental categories. It however presents higher impact scores for climate change and resource depletion compared to some reusable scenarios, particularly the portal frame with the C25/30 keying used to cover the crossed rebars. The construction stage of the couple of reusable portal frames (C25/30 crossed rebars and C60-75 straight rebars) presents results differing from the other pair (C40/50 crossed rebars and C60/75 crossed rebars), for all impacts except those of resource depletion but with deviations inferior to 20%. The former seems to have less impact than the latter. It should be noted that impact scores between scenarios differ by less than 10%.

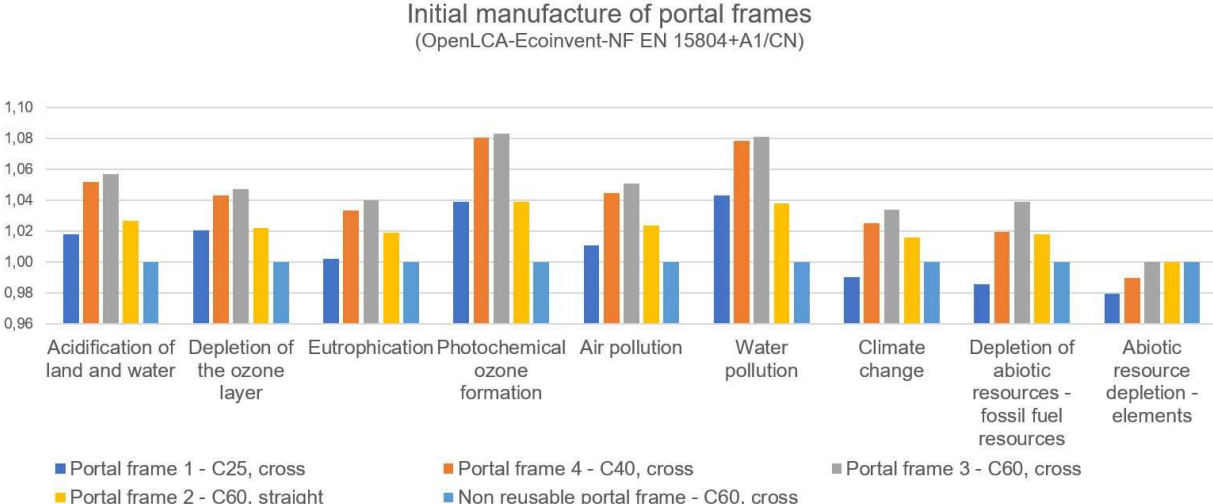


Fig. 7. Environmental impact scores of the portal frames' initial production stage.

3.2. Deconstruction and reconstruction of portal frames

Considering the impacts of the deconstruction/reconstruction stage reverses the trends. The non-reusable portal frame is this time significantly more impacting for all indicators. Its scores are 3 to 10 times higher than reused scenarios scores, depending on the environmental category. The scores of reused portals are greatly reduced since raw material

extraction and manufacturing stages are attributed to the first life cycle and no longer included in the system. In that sense, the difference of impacts between the portal frames with C40/50 and C60/75 keying and C25/30 crossed rebars and C60/75 straight rebars scenarios is reduced (Figure 8).

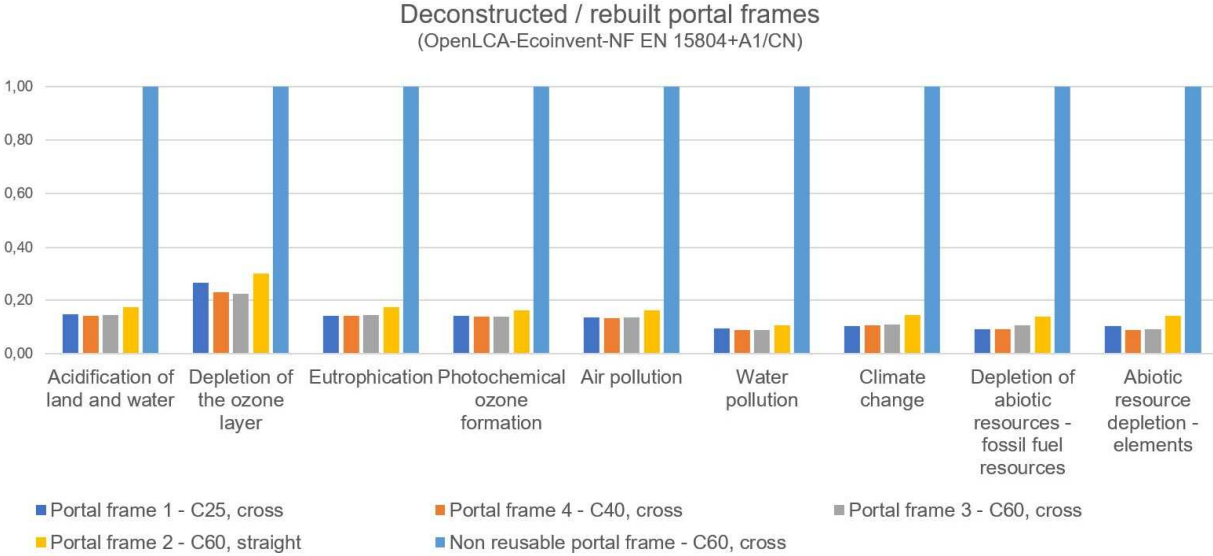


Figure 8: Environmental impact scores of the portal frames' deconstruction/reconstruction stage

A detailed analysis for the deconstruction/reconstruction stage has been carried out on the reused portal frames in order to identify the major contributing processes (excluding raw material extraction and manufacturing). Scenario 1, with the C25/30 keying, is presented in Figure 9, the other reused portal frames presenting the same trends. It can be noted that the machining process is very impactful for most of the environmental categories, except for "Depletion of the ozone layer", where transport is dominant, and "Depletion of abiotic resources - elements", where only material is contributing. For "Climate change" and "Abiotic resource depletion - fuels", the main contributors, namely machining, energy, materials, are more balanced. Reuse significantly reduces the share of materials in the global environmental impacts of portals. The next contributor to act on is machining, then energy supply.

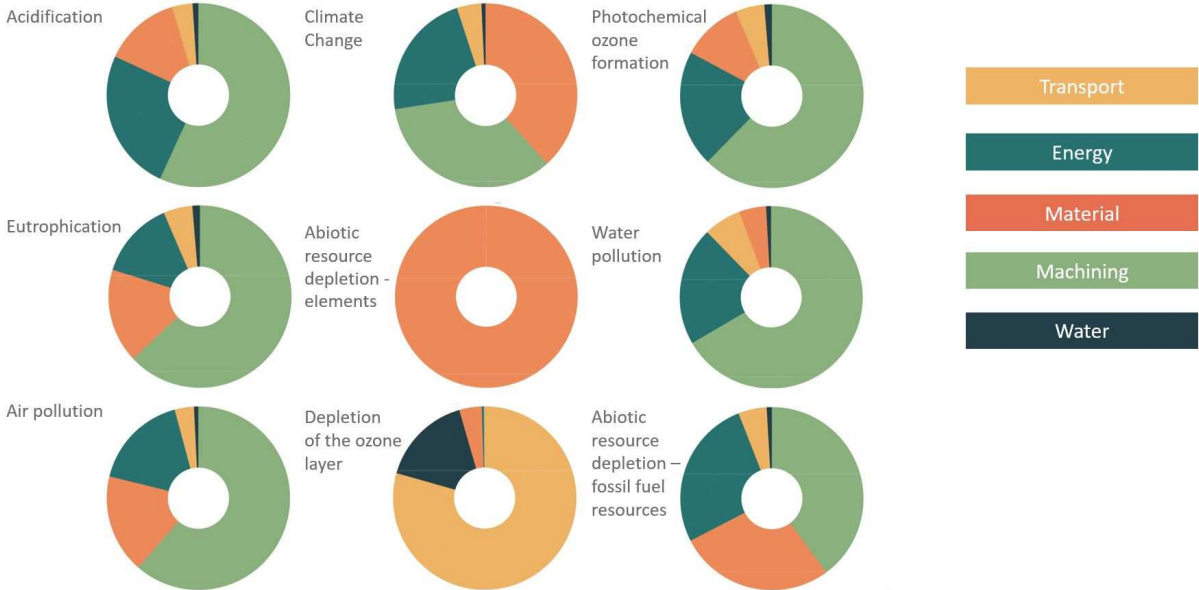


Figure 9: Contribution analysis for the portal frame with the C25/30 keying (deconstruction/ reconstruction process)

3.3. Extrapolation to the building

To assess the effect of scale on the impact assessment results, the evaluation is performed at building scale. The building considered is composed of the portal frames studied previously. It consists of 10 floors mid-rise building, composed of 640 beams and 420 columns. Two hypothetical alternatives are compared (Figure 10):

1) a scenario with one cycle with a building composed of newly manufactured portal frames 1 (with C25/30 dismountable assemblies, Table 1) and a cycle with a “reused” building composed of the same portal frames 1, reused;

2) a scenario of two cycles of new building composed of non-reusable portal frames cast-in-place with C60/75 concrete.

Given the concrete grade used for the portal frames, a structural service life of 100 years is planned. High performance concrete (HPC) such as C60/75 is suitable for such a project. Its low permeability and low porosity are responsible for its long service life. Indeed, ion diffusion is very slow in HPC. It presents a durability much superior to an ordinary concrete (Aïtcin 2001; Baroghel-Bouny 2004, Malier et al 1992). Given the durability of reinforced concrete buildings built at the beginning of the 20th century, a lifetime between 50 and 100 years is expected for an ordinary/normal grade concrete (Marie Victoire et al 2006). Lifetime (understood as the time before major repairs) of structures mainly undergoing carbonation risks, could therefore be of the order of 50-100 years for a reinforced concrete, 200 years for a high performance concrete, or even 300 years and more for an ultra-high performance fiber-reinforced concrete (Toutlemonde et al 2009; Resplendino et al 2009; AFGC 2013).

The assessment is then conducted over two successive usage cycles of 50 years each:

- First usage cycle: the two original buildings are constructed with cast-in-place concrete.
- Second usage cycle: the reused building is considered prefabricated, since it relies on prefabrication methods to assemble the elements already manufactured in the first cycle. For the second scenario with new buildings, we consider a cast in place fabrication for the new cycle. Slabs are not part of the study, only the elements constituting the portal frame (beams and columns) are analyzed. The crane operating times are those proposed on the IUT Robert Schuman website and distinguish between the time required to install a prefabricated element and the time required to cast in place. The average power of the crane is 40 kW (power supply) per hour and for a 7-hour working day, according to the Potain website.
- For the end-of-life, the building structure is demolished and concrete is processed for recycling. To that aim, we use the felling data proposed by Brière (2016).

These buildings are an adaptation, at scale 1, of the reinforcement framework repeating the portal frame designed experimentally at scale 1/3. Resizing is necessary to move to scale 1 and to allow realistic reinforcement rates since shifting from 1/3 scale to scale 1 is not proportional. For hydrodemolition, the energy consumption per m³ of hydrodemolished concrete on the 1/3 scale portal frame is retained to be applied to the volume to be hydrodemolished on the reusable building.

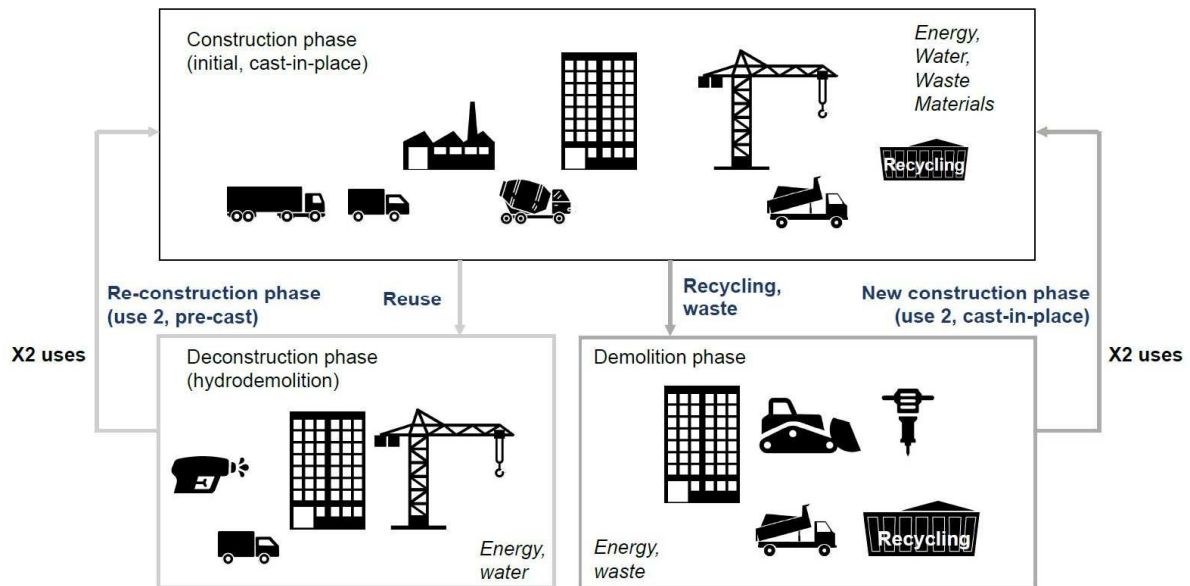
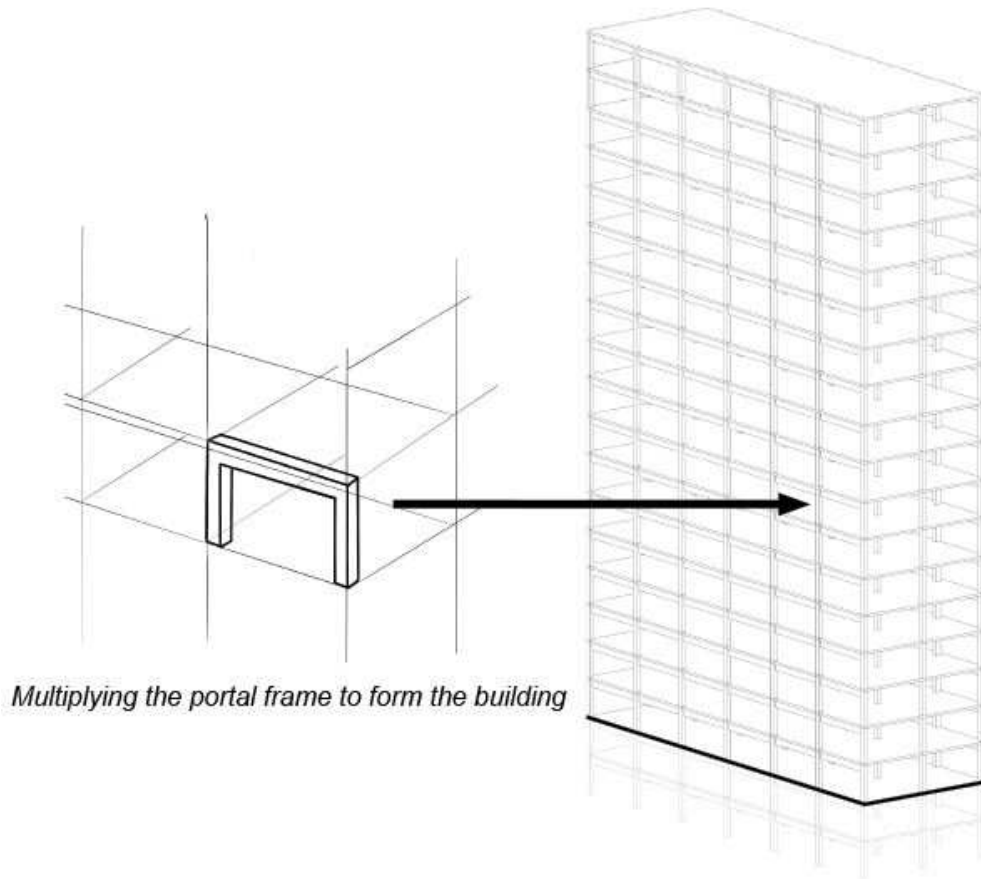


Fig. 10. Comparing new and reusable buildings

The impact scores per category are shown in Figure 11. The dark colors correspond to the reusable version and the light colors to the non-reusable version of the building. The two successive cycles of use and the end of life are shown in blue, grey and red respectively. The results are cumulated with each new cycle. It can be noted that, for the first usage cycle, the new building has globally lower impacts compared to the reusable building: reusability involves more reinforcement to ensure the demountability and stability of the deconstructable assembly. After 2 usage cycles, integrating respectively one reuse cycle and one ultimate

end of life for the reusable scenario, and two constructions and two ends of life for the non-reusable scenario, the reusable building appears to be significantly less impacting than the new building for most of the impact categories. With the exception of ozone layer depletion for which the difference is about 16%, impact scores are lower by 38% to 67%. For this case study, reuse of load-bearing elements on a building scale is much more virtuous than traditional cast-in-place construction. The trend is true from the first reuse cycle and confirmed after two reuse cycles (Figure 12).

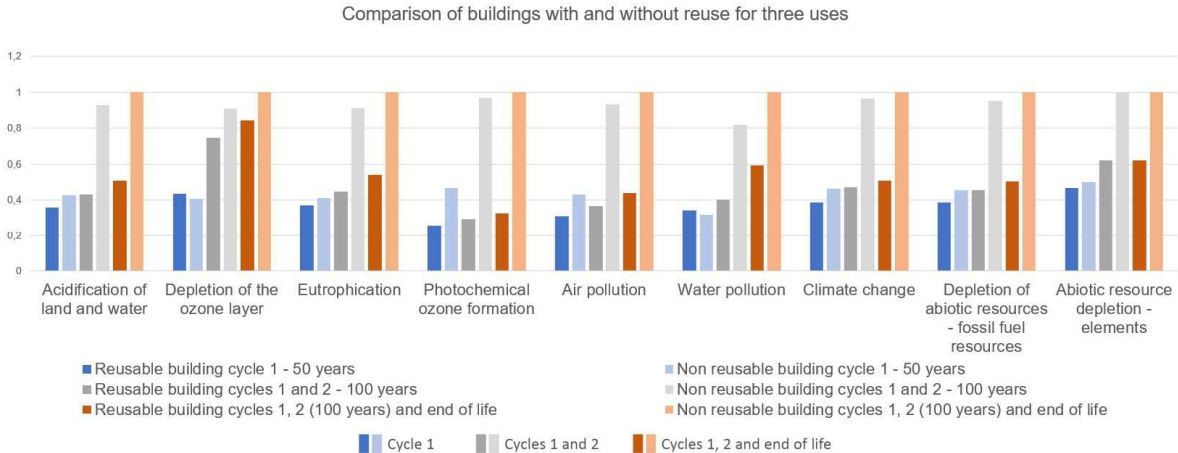


Fig. 11. Environmental impacts between reusable and new building for 2 usage cycles (50 years each) and an ultimate end of life. Comparison between buildings with reused portal frames and buildings with new portal frames, according to the impact indicators of NF/EN 15804+A1/CN

4. Discussion

4.1 Functional downgrading of the portal frame and losses

At the scale of the structural element, we considered the portal frame to keep the same quality of service during the different usage cycles. In order to study the impact of a functional downgrading of the portal frame, we assume that the reusable portal frame is subject to an additional safety factor at each reuse. The structural engineer who integrates a reused element in a new structure may take additional precautions in its dimensioning. Thus, a functional downgrading could progressively reduce artificially the structural capacity of the portal frame. One could therefore consider a full capacity in cycle 1, then a degressive capacity with each new cycle of use.

The environmental performance of the reusable portal frame is also influenced by the loss coefficient. The differences in impact scores between the reusable portal frame and the non-reusable ones are less important considering losses. Considering a loss coefficient of 20%, the reused portal frame still remains environmentally favorable. For a loss coefficient of 30%, the new portal frame becomes more favorable compared to the re-used portal frame after 6 usage cycles (Figure 12).

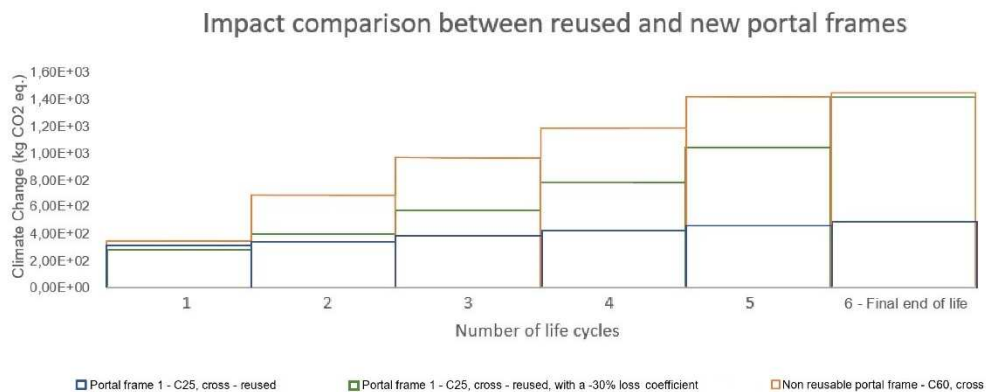


Fig. 12. Comparison of climate change impact scores for the reusable and non-reusable portal frames over 6 life cycles, a) without loss ; b) integrating a loss coefficient of 30%.

4.2 Allocating impacts between usage cycles

So far, allocation of environmental impacts between the different usage cycles was dealt with using the cut-off approach (Schrijvers et al 2016). However, environmental benefits of reuse could be distributed in a different way. According to the previous results, for reused portal frames with limited functional downgrading and losses, most of the impacts occur during the first use cycle (Figures 11 and 12). Reuse becomes environmentally "profitable" from the second usage cycle on, i.e. after a first reuse. However, if the owner of the building of the first usage cycle is different from the owner of the building of the second usage cycle, then the first owner assumes the environmental burden of the DfReu implementation, higher than for a traditional construction, with additional study costs. The second owner benefits from this design by reusing the structural components and therefore is the sole benefactor of the efforts made by the initial owner. In order not to disadvantage the first owner and to encourage the design of reusable buildings, the final benefit of reuse, after several usage cycles, could be distributed in a fairer manner. On the other hand, it could also be argued that the owner reusing structural elements takes a risk in implementing such practices. Characterizing the reusable elements has also a cost. The additional investment for a reuse operation could thus be compensated by an environmental bonus, addressed by an appropriate allocation method.

Several options are possible to distribute the environmental impacts or to evaluate a bonus. For example, De Wolf et al (2020) propose several types of allocation to distribute the impacts of reuse and to visualize the variations in impacts per cycle, according to the adopted distribution. First of all, in the context of a design with a reuse perspective, it is indeed the first decision-maker who must be convinced to invest, which is a *sine qua non* condition for the subsequent cycles of use to take place. The allocation principle could be the subject of a calculation rule set by the legislators to encourage virtuous practices. Xia et al (2021) have also shown that allocating environmental impacts based on the degradation process of components can promote the adoption the decision makers of concrete component reuse strategies.

5. Practical implications of the present study

LCA has been applied on a disassembly technic of embedded connections, using hydrodemolition and validated through a specifically designed experimental protocol. This technic constitutes a technological leap in terms of reinforced concrete structure reuse. It proposes a connection principle economically and environmentally interesting. Previous results show the conditions for which implementing DfReu can lead to significant environmental benefits. Below are given some recommendations addressed to the structural designer.

From a structural point of view, the usage of used parts, in good condition after 100 years of service, encourages the utilization of HPC. HPC has proven its high durability (Aïtcin 2001; Baroghel-Bouny 2004). The main ageing factor of a building being carbonation, HPC goes through a slow ageing process in carbonating environments, presuming a lifetime without maintenance of several hundred years. The work presented here anticipated this result since beams and columns in the study are formulated with HPC of C60/75 grade concrete. Results of the study go against current presuppositions regarding the choice of construction materials for buildings. Concrete is known as an environmentally burdensome matter. Many ecodesigners consider that low carbon concrete has to be used in priority to obtain environmental benefits at the scale of a building structure. In addition to being limited by constitutive resources (particularly blast furnace slags), this type of concrete, with normal resistance, has however mostly a limited durability and does not reach the benefits obtained with HPC. Similar conclusions can be found for civil works (Habert et al 2012).

Without taking into account functional downgrading and material losses, impact scores after a first reuse cycle are significantly reduced for all categories. Concrete, and particularly HPC, has durability qualities allowing to undergo several usage cycles. This study proves that reusing is an important way to reduce the environmental impacts of concrete structural elements. The effectiveness of environmental benefits however depends on these two parameters. Guidance should then be provided to insure that future reuse practices will actually provide the expected benefits. It could take the form of maximum loss rate and functional downgrading for a given number of planned usage cycles. This has to be conducted in parallel to full-scale experiments of load-bearing elements disassembly to estimate the realistic rates that can be obtained when deconstructing a building.

Such conclusion seems only possible with the hydrodemolition process, since it keeps the steel rebars intact. The feasibility of the technics depends on the availability of water. This can be a problem in areas where water is a physically or economically scarce resource. Further assessments should take water consumption into account and include the characterization of potential water depletion problems (Boulay et al 2018).

6. Conclusions and future prospects

Different strategies are encouraged to achieve sustainable development goals and mitigate climate change. In the construction sector, improvements are expected through the implementation of low carbon or circular strategies. The reuse of construction materials and structural elements has been identified as an interesting driver to reduce GHG emissions, along with the preservation of natural resources and decrease in waste generation. However, these effects must be rigorously studied and quantified by recognized and comprehensive methods. Facing the lack of data to conduct a proper LCA, we proposed to operationalize the DfReu concept through an experimental case study in which a reinforced concrete portal frame, designed to be reusable, was built, deconstructed and reused. In addition to validating the technical feasibility of portal frame reuse, the subsequent environmental assessment

demonstrates the environmental benefits of reuse practices despite certain constraints such as stringent deconstruction.

Reuse of load-bearing elements is favorable as it reduces the environment scores of several categories as early as the second cycle of use. Reuse is significantly more advantageous when the reuse cycles are multiplied. Functional downgrading and losses between usage cycles should however be considered, as it limits the environmental performances of reuse compared to traditional single use practices. The findings of our experimental study need to be confirmed on a larger scale in order to provide sound evidence for designers and legislators and to encourage appropriate reuse practices. Further research is needed to precise the maximum rates of material losses and functional downgrading that guaranty the achievement of reuse environmental benefits. Research is also needed to explore the long term structural behavior of the proposed embedded connections, in order to discuss the validity of adding extra safety factor for each reuse cycle.

The impact scores presented above are calculated for a system limited to the load-bearing structure of a mid-rise building. Slabs are not considered in the assessment and should be integrated in future work, as they constitute an important volume of constructive structures. The data used are experimental, extrapolated at the scale of the building. Although the deconstruction and reconstruction techniques experimented in the case study are close to the usual on-site techniques, the reduced prototypes constitute a special case. These results can therefore not be generalized to all types of building. Specific LCA should be carried out for other structural elements and building types. Also, hybrid scenarios with different rates of reused structural components (Brütting et al 2020) or replacement rates (Goulouti et al 2020; Morales et al 2020) could be tested.

It is however possible to draw some general recommendations. The lifespan of materials, structural elements and buildings should be extended as much as possible. The optimal solution is to keep the buildings operating to lengthen the building usage cycles and reduce the number of reuses. The notion of time and the anticipation of future uses has proven to be limited with current LCA applications. Prospective scenarios regarding the different possible usages and functions of the building (identical use, misappropriation, downgrading, iterative passages of products...) should be further explored.

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References

- AFNOR, 2016. NF EN 15804/CN, Sustainability of construction works - Environmental product declarations - Core rules for the product category of construction products - National addition to NF EN 15804+A1, AFNOR. AFNOR, 2014. NF EN 15804+A1, Sustainability of construction works - Environmental product declarations - Core rules for the product category of construction products, AFNOR.
- Aïtcin, P.C., 2001. *Bétons haute performance*, Eyrolles, Paris.
- Akadiri, P.O., Chinyio, E.A., Olomolaiye, P.O., 2012. Design of A Sustainable Building: A Conceptual Framework for Implementing Sustainability in the Building Sector. *Buildings*. 2, 126-152. <https://doi.org/10.3390/buildings2020126>.
- Anderson, J.E., Silman, R. A Life Cycle Inventory of Structural Engineering Design, Strategies for Greenhouse Gas Reduction. *Structural Engineering International*. 3, 283-288. <https://doi.org/10.2749/101686609788957946>.
- Barhogel-Bouny, V. (2004),
- Bertin, I., 2020. *Conception des bâtiments assurant leur réversibilité, leur déconstruction et leur réemploi, méthodologie de suivi et évaluation environnementale sur les cycles de vie,*" Université Paris-Est, Ecole Doctorale Sciences, Ingénierie et Environnement, Thèse de Doctorat, Champs-sur-Marne.
- Bertin, I., Mesnil, R., Jaeger, J.-M., Feraille, A., Le Roy, R., 2020, A BIM-Based Framework and Databank for Reusing Load-Bearing Structural. *Sustainability*. 8(12) 3147. doi :10.3390/su12083147.
- Blengini, G.A., Di Carlo, T., 2010. The changing role of life cycle phases, subsystems and materials in the LCA of low energy buildings. *Energy Build.* 42, 869–880. <https://doi.org/10.1016/j.enbuild.2009.12.009>.
- Blengini, G.A., 2009. Life cycle of buildings, demolition and recycling potential: A case study in Turin, Italy. *Building and Environment*. 44(2), 319-330. <https://doi.org/10.1016/j.buildenv.2008.03.007>.
- Boulay, AM., Bare, J., Benini, L. et al., 2018. The WULCA consensus characterization model for water scarcity footprints: assessing impacts of water consumption based on available water remaining (AWARE). *Int. J. Life Cycle Assess.* 23, 368–378. <https://doi.org/10.1007/s11367-017-1333-8>.
- Brière, R., 2016. *Etude ACV des chantiers de démolition en vue de la préservation des ressources. Focus sur les procédés de transport et de décharge.* Université Paris-Est, Ecole Doctorale Sciences, Ingénierie et Environnement, Thèse de Doctorat.
- Brütting, J., Vandervaeren, C., Senatore, G., De Temmerman, N., Fivet, C., 2020. Environmental impact minimization of reticular structures made of reused and new elements through Life Cycle Assessment and Mixed-Integer Linear Programming. *Energy and Buildings*. 215, 109827. doi: 10.1016/j.enbuild.2020.109827.
- Brütting, J., De Wolf, C., Fivet, C., 2019. The reuse of load-bearing components. SBE19 Brussels BAMB-CIRCPATH IOP Conf. Series: Earth and Environmental Science 225, no. 012025, p. 8. doi: 10.1088/1755-1315/225/1/012025.
- Brütting, J., G. Senatore, G., Fivet, C., 2018. Optimization Formulations for the Design of Low Embodied Energy Structures Made from Reused Elements. *Advanced Computing Strategies for Engineering*.
- Brütting, J., Desruelle, J., Senatore, G., Fivet, C., 2019. Design of Truss Structures Through Reuse. *Structures*. 18, 128-137. doi: 10.1016/j.istruc.2018.11.006.
- Butera, S., 2015. Life cycle assessment of construction and demolition waste management. *Waste management*. 44, 196-205. <https://doi.org/10.1016/j.wasman.2015.07.011>.
- Buyle, M., Galle, W., Debacker, W., Audenaert, A., 2019. Sustainability assessment of circular building alternatives: Consequential LCA and LCC for internal wall assemblies as a case study in a Belgian context. *Journal of Cleaner Production*. 218, 141-156. doi: 10.1016/j.jclepro.2019.01.306.
- Cabeza, L.F., Rincón, L., Vilariño, V., Pérez, G., Castell, A., 2014. Life cycle assessment (LCA) and life cycle energy analysis (LCEA) of buildings and the building sector:

- A review. *Renewable and Sustainable Energy Reviews*. 29, 394–416. doi: 10.1016/j.rser.2013.08.037.
- Cai, G., Waldmann, D., 2019. A material and component bank to facilitate material recycling and component reuse for a sustainable construction: concept and preliminary study. *Clean Technologies and Environmental Policy*. 21, 2015-2032. doi: 10.1007/s10098-019-01758-1.
- Cavalliere, C., Habert, G., Dell'Osso, G.R., Hollberg, A., 2018. Continuous BIM-based assessment of embodied environmental impacts throughout the design process. *Journal of Cleaner Production*. 211, 941-952. doi: 10.1016/j.jclepro.2018.11.247.
- Crowther, P., 2001. Developing an inclusive model for design for deconstruction. *Proceedings of the CIB World Building Congress 6 Task Group 39: Deconstruction, Wellington*.
- De Larrard F., Sedran T., 1996. Computer-Aided Mix Design: Predicting Final Result. *Concrete International*. 12(18), 39-41.
- De Wolf, C., Hoxha, E., Fivet, C., 2020). Comparison of environmental assessment methods when reusing building components: A case study. *Sustainable Cities and Society*. 61, 102322. <https://doi.org/10.1016/j.scs.2020.102322>.
- Desbois, T., 2017. Rapport du Cerema. Méthode d'évaluation environnementale sous OpenLCA selon la norme NF EN 15804+A1 et la norme complémentaire NF EN 15804/CN, Saint-Brieuc: Cerema / DTerOuest / Laboratoire de Saint-Brieuc.
- Densley Tingley, D., Davison, B., 2012. Developing an LCA methodology to account for the environmental benefits of design for deconstruction. *Building and Environment*. 57, 387-395. doi: 10.1016/j.buildenv.2012.06.005.
- Durmisevic, E. Yeang, K., 2009. Designing for disassembly (DfD). *Architectural Design*. 79, 134–137. <https://doi.org/10.1002/ad.994>.
- Eberhardt, L.C.M., Birgisdottir, H., Birkved, M. 2019. Life cycle assessment of a Danish office building designed for disassembly. *Building Research and Information*. 47(6). doi: 10.1080/09613218.2018.1517458.
- Eberhardt, L.C.M., Birgisdottir, H., Birkved, M, 2019. Comparing life cycle assessment modelling of linear vs. circular building components. *IOP Conferences Series: Earth and Environmental Science*. 225, 012039. doi: 10.1088/1755-1315/225/1/012039
- EEA, 2016. Circular economy in Europe, Developing the knowledge base, European Environment Agency, EEA Report No 2..
- European Commission, 2020. Circular Economy Action Plan - For a cleaner and more competitive Europe.
- Eurostat, 2019. Generation of waste by waste category, hazardousness and NACE Rev. 2 activity. https://appsso.eurostat.ec.europa.eu/nui/show.do?dataset=env_wasgen&lang=en. (accessed 25 Mar 2021).
- FCBA, Institut Technologique, 2017. Vision d'ensemble, Rapport annuel 2016. [Online]. Available: https://www.fcba.fr/sites/default/files/files/RA_2016.pdf.
- Ferreira Dias Morales, M., Reguly, N., Kirchheim, A.P., Passuello, A., 2020. Uncertainties related to the replacement stage in LCA of buildings: A case study of a structural masonry clay hollow brick wall. *Journal of Cleaner Production*. 251, 119649. doi: 10.1016/j.jclepro.2019.119649.
- Fivet, C., 2019. Design of Load-Bearing Systems for Open-Ended Downstream Reuse. in *SBE19 Brussels BAMB-CIRCPATH*, IOP Conf. Series: Earth and Environmental Science 225 012031, Brussels. doi: 10.1088/1755-1315/225/1/012031.
- Gorgolewski, M., 2018. Resource salvation, The architecture of Reuse, Wiley Blackwell.
- Goulouti, K., Padey, P., Galimshina, A., Habert, G., Lasvaux, S., 2020. Uncertainty of building elements' service lives in building LCA & LCC: What matters? *Building and Environment* 183, 106904. doi: 10.1016/j.buildenv.2020.106904.
- Habert, G., Arribe, D., Dehove, T., Espinasse, L., Le Roy, R., 2012. Reducing environmental impact by increasing the strength of concrete: quantification of the improvement to concrete bridges. *Journal of Cleaner Production*. 35, 250-262. <https://doi.org/10.1016/j.jclepro.2012.05.028>.

- Hoxha, E., Habert, G., Lasvaux, S., Chevalier, J., Le Roy, R., 2016. Influence of construction material uncertainties on residential building LCA reliability. *Journal of Cleaner Production*. 144, 33-47. doi: 10.1016/j.jclepro.2016.12.068.
- Iacovidou, E., Purnell, P., 2016. Mining the physical infrastructure: Opportunities, barriers and interventions in promoting structural components reuse. *Science of the Total Environment*. 557-558, 791-807. doi: 10.1016/j.scitotenv.2016.03.098.
- Ibrahim, M., 2016. Estimating the sustainability returns of recycling construction waste from building projects. *Sustainable Cities and Society*. 23, 78-93. doi: 10.1016/j.scs.2016.03.005.
- Irle, M., Privat, F., Couret, L., Belloncle, C., Déroutbaix, G., Bonnin, E. Cathala, B. 2019. Advanced recycling of post-consumer solid wood and MDF. *Wood Material Science and Engineering*. 14(1), 19-23. doi: 10.1080/17480272.2018.1427144.
- Kaethner, S., BurrIDGE, J., 2012. Embodied CO₂ of structural frames. *The Structural Engineer*. 90(5), 33-40.
- Kiss, B., Röck, M., Passer, A., Szalay, Z., 2019. A cross-platform modular framework for building Life Cycle Assessment. *SBE D-A-CH 19 IOP Conf. Series: Earth and Environmental Science* 323. 012103, 10. doi: 10.1088/1755-1315/323/1/012103.
- Klingmair, M., Sala, S. randão, M., 2013. Assessing resource depletion in LCA: a review of methods and methodological issues. *The International Journal of Life Cycle Assessment*, 19, 580–592. doi: 10.1007/s11367-013-0650-9.
- Koutamanis, A., van Reijn, B., van Bueren, E., 2018. Urban mining and buildings: a review of possibilities and limitations. *Journal for Resource Conservation and Recycling*. 138, 32-39. <https://doi.org/10.1016/j.resconrec.2018.06.024>.
- Lankhorst, G.J., Arts, J., Terwel, K.C., Jonkers, H.M., 2019. Life Cycle Analysis: Load-Bearing Structures Of High-Rise Buildings in Western Europe. *CTBUH Journal*. 3, 28-35.
- Lismont, A., Allacker, K., 2019. Turning the existing building stock into a resource mine: proposal for a new method to develop building stock models. *SBE D-A-CH 19 IOP Conf. Series: Earth and Environmental Science* 323, no. 012070, p. 10. doi: 10.1088/1755-1315/323/1/012070.
- Malier, Y., 1992. *High Performance Concrete. From material to structure*, Chapman & Hall, London.
- Marie Victoire, E., Cailleux, E., Teixier A., 206. Carbonation and historical building made of concrete. *J. Phys. IV France*. 136, 305–318. <https://doi.org/10.1051/jp4:2006136031>.
- Mastrucci, A., Marvuglia, A., Popovici, E., Leopold, U., Benetto, E., 2017. Geospatial characterization of building material stocks for the life cycle assessment of end-of-life scenarios at the urban scale. *Resources, Conservation and Recycling*. 123, 54-66. <https://doi.org/10.1016/j.resconrec.2016.07.003>.
- Marzouk, M., Mohammed Abdelkader, E., Al-Gahtani, K., 2017. Building information modeling-based model for calculating direct and indirect emissions in construction projects. *Journal of Cleaner Production*. 152, 351-363. doi: 10.1016/j.jclepro.2017.03.138.
- Momber, A. (2005), *Hydrodemolition of Concrete Surfaces and Reinforced Concrete*, 1st Edition, eBook ISBN: 9780080534305.
- Najjar, M., Figueiredo, K., Palumbo M., Haddad, A., 2017. Integration of BIM and LCA: Evaluating the environmental impacts of building materials at an early stage of designing a typical office building. *Journal of Building Engineering*. 14, 115-126. doi: 10.1016/j.jobe.2017.10.005.
- Nußholz, J.L., Rasmussen, F.N., Whalen, K., Plepys, A., 2020. Material reuse in buildings: Implications of a circular business model for sustainable value creation. *Journal of Cleaner Production*. 245, 118546. doi: 10.1016/j.jclepro.2019.118546.
- Palacios-Munoz, B., Peuportier, B., Gracia-Villa, L., López-Mesa, B., 2019. Sustainability assessment of refurbishment vs. new constructions by means of LCA and durability-based estimations of buildings lifespans: A new approach. *Building and Environment*. 160, 106203. doi: 10.1016/j.buildenv.2019.106203.
- Peuportier, B., Kohler, K., Boonstra, C., 1997. European project REGENER, life cycle analysis of buildings. 2nd International Conference "Buildings and the Environment..

- Peuportier, B., Thiers, S., Guiavarch, A., 2013. Eco-design of buildings using thermal simulation and life cycle assessment. *Journal of Cleaner Production*. 39, 73–78.
- Privat, F., 2019. Faisabilité du recyclage en boucle fermée des déchets post-consommateurs en bois massif. Ecole Centrale de Nantes, Université Bretagne Loire, Ecole Sciences pour l'ingénieur, Thèse de Doctorat, Nantes.
- Qarout, L., 2017. Reducing the Environmental Impacts of Building Materials: Embodied Energy Analysis of a High-performance Building. University of Wisconsin Milwaukee, PhD Thesis.
- Rasmussen, F., Birkved, M. Birgisdóttir, H., 2019. Upcycling and Design for Disassembly – LCA of buildings employing circular design strategies. *IOP Conf. Ser.: Earth Environ. Sci.* 225 012040.
- Reap, J., Roman, F., Duncan, S., Bras, B., 2008. A survey of unresolved problems in Life Cycle Assessment - Part 2: impact assessment and interpretation. *The International Journal of Life Cycle Assessment*. 13(5), 374-388. doi: 10.1007/s11367-008-0009-9.
- Resplendino, J. «Introduction : Qu'est ce qu'un BFUP,» 17 Novembre 2009. [En ligne]. Available: https://www.afgc.asso.fr/app/uploads/2009/12/1.1_Resplendino.pdf. [Accès le 7 Juin 2020].
- Röck, M., Mendes Saade, M. R., Balouktsi, M., Rasmussen, F.N., Birgisdottir, H., Frischknecht, R. Habert, G. Lützkendorf, T., Passer, A., 2020. Embodied GHG emissions of buildings – The hidden challenge for effective climate change mitigation. *Applied Energy*. 258, 114107. <https://doi.org/10.1016/j.apenergy.2019.114107>.
- Shahmir Nizam, R., Zhang, C., Tian, L. 2018. A BIM based tool for assessing embodied energy for buildings. *Energy & Buildings*. 170, 1-14. doi: 10.1016/j.enbuild.2018.03.067.
- Sandin, G., Peters, G., Svanström, M., 2014. Life cycle assessment of construction materials: The influence of assumptions in end-of-life modelling. *The International Journal of Life Cycle Assessment*. 19(4), 723-731. <https://doi.org/10.1007/s11367-013-0686-x>.
- Schrijvers, D., Loubet, P., Sonnemann, G., 2016. Critical review of guidelines against a systematic framework with regard to consistency on allocation procedures for recycling in LCA. *The International Journal of Life Cycle Assessment*. 21(7), 994-1008. doi: 10.1007/s11367-016-1069-x.
- G. d. t. B. AFGC, «Bétons fibrés à ultra-hautes performances, Recommandations,» Juin 2013. [En ligne]. Available: <https://www.afgc.asso.fr/app/uploads/2007/10/Recommandations-BFUP-Juin-2013.pdf>. [Accès le 7 Juillet 2020].
- Toutlemonde, F., Carcasses, M. Lion, M., 2009. Durabilité et évolution in-situ des caractéristiques d'un BFUP : retour d'expérience sur poutrelles dans un aérofrigorifère. BFUP 2009, Nov 2009, France.
- UNEP, 2021. Global Status Report for Buildings and Construction: Towards a Zero-emission, Efficient and Resilient Buildings and Construction Sector. Nairobi.
- UNEP, 2019. Sand and sustainability: Finding new solutions for environmental governance of global sand resources. GRID-Geneva, United Nations Environment Programme, Geneva.
- Veselka, J., Růžička, J., Lupíšek, A., Hájek, P., Mančík, S., Žďára, V., Široký, M., 2019. Connecting BIM and LCA: The Case Study of an Experimental Residential Building. SBE D-A-CH 19 IOP Conf. Series: Earth and Environmental Science 323, no. 012106, p. 6. doi: 10.1088/1755-1315/323/1/012106.
- Vis, M., Manteau, U., Allen, B., 2016. Study on the optimised cascading use of wood. European Commission, Brussels.
- Wong, J., Zhou, J., 2015. Enhancing environmental sustainability over building life cycles through green BIM: A review. *Automation in Construction*. 57, 156-165. <https://doi.org/10.1016/j.autcon.2015.06.003>.
- WWF, "Cascading use of wood products," [Online]. Available: <https://www.wwf.eu/?263091/Cascading-use-of-wood-products-report>. [Accessed 27 April 2021].

Xia, B., Ding, T., Xiao, J., 2020. Life cycle assessment of concrete structures with reuse and recycling strategies: A novel framework and case study. *Waste Management*. 105, 268-278. <https://doi.org/10.1016/j.wasman.2020.02.015>.

Xiao, J., Ding, T., Zhang, Q., 2017. Structural behavior of a new moment-resisting DfD concrete connection. *Engineering Structures*. 132, 1-13. <https://doi.org/10.1016/j.engstruct.2016.11.019>.

Yellishetty, M., Mudd, G., Ranjith. P.G, 2011. The steel industry, abiotic resource depletion and life cycle assessment: A real or perceived issue? *Journal of Cleaner Production*. 19(1), 78-90. doi: 10.1016/j.jclepro.2010.08.020.

Yung, P., Wang, X., 2014. A 6D CAD Model for the Automatic Assessment of Building Sustainability. *International Journal of Advanced Robotic Systems*. 11, 8. doi: 10.5772/58446.

Web references

Institut Universitaire de Technologie Robert Schuman (IUT RS)

R. S. IUT. [Online]. Available: <http://polyvert.iutrs.unistra.fr/temps-unitaires-de-cycles-de-grue/>. [Accessed 5 February 2020].

Potain, "<https://docplayer.fr/8566860-Potain-alimentation-electrique-gamme-2012-guide-produit-ref-608-2012-04-fr.html>," [Online]. Available: <https://docplayer.fr/8566860-Potain-alimentation-electrique-gamme-2012-guide-produit-ref-608-2012-04-fr.html>. [Accessed 16 April 2019].

[IFSTTAR, «Un béton "vert" est-il possible?,» 5 novembre 2018. [En ligne]. Available: https://www.ifsttar.fr/fileadmin/redaction/dossiers-thematiques/infrastructures/betonvert/11364_Beton_Vert_FR_interactif.pdf. [Accès le 18 septembre 2019].].

Figure captions

Figure 1: Average breakdown of embodied energy for building elements, based on [17]Qarout (2017) and [18]Kaethner and Burrige (2012).

Figure 2: Case study. Left: portal showing the rebars overlap depending on concrete strength; Right: result of Reinforcements after the hydro-deconstruction process.

Figure 3: Summary of the testing experimental protocol for the 4 portal frames.

Figure 4: System boundaries of the studied portal frame.

Figure 5: Data collected during the construction and deconstruction processes

Figure 6: LCA modeling for the manufacture of portal frame 1, initial use. Processes from the ecoinvent data base are indicated in italic. The other processes were specifically created for the study, with the exception of the processes for cement and aggregates provided by French professional associations.

Figure 7: Environmental impact scores of the portal frames' initial production stage.

Figure 8: Environmental impact scores of the portal frames' deconstruction/reconstruction stage.

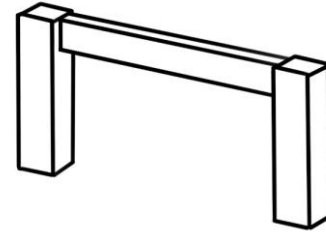
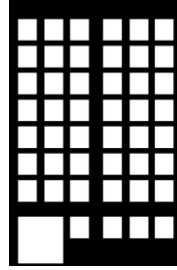
Figure 9: Contribution analysis for the portal frame with the C25-30 keying (deconstruction/reconstruction process)

Figure 10: Comparing new and reusable buildings

Figure 11: Environmental impacts between reusable and new building for 2 usage cycles (50 years each) and an ultimate end of life. Comparison between buildings with reused portal frames and buildings with new portal frames, according to the impact indicators of NF/EN 15804+A1/ CN.

Figure 12: Comparison of climate change impact scores for the reusable and non-reusable portal frames over 6 life cycles, a) without loss; b) integrating a loss coefficient of 30%.

CO₂



Carbon neutrality to be reached

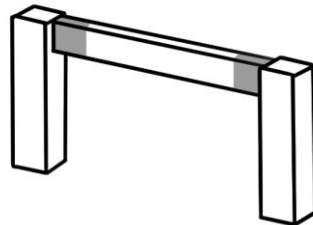
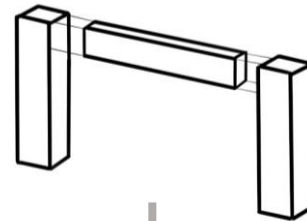
The building and construction sector represents 33% to 40% of GHG emissions

The main part of GHG is due to the structure of a building

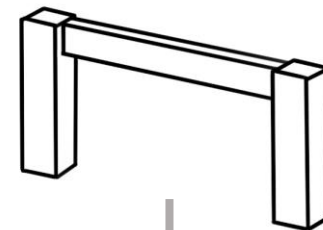
About 80% of the French building stock is made of cast-in-place concrete

Scenarios to be compared

Reuse



Recycling



LCA demonstrating the significant benefits of reuse after an experiment on a reinforced concrete portal frame.

Conclusion: Design for Reuse (DfReu) should be applied to the construction sector to reduce its environmental impacts.

