*E. Quéheille, A. Ventura, N. Saiyouri, and F. Taillandier, "A Life Cycle Assessment model of End-of-life scenarios for building deconstruction and waste management," J. Clean. Prod., vol. 339, p. 130694, Mar. 2022, doi: 10.1016/j.jclepro.2022.130694*

# A Life Cycle Assessment model of End-of-life scenarios for building deconstruction and waste management

Eva Quéheille[1*], Anne Ventura[1], Nadia Saiyouri[2], Franck Taillandier[3]

[1]MAST/GPEM Campus of Nantes, Gustave Eiffel University, Bouguenais, France, [2]University of Bordeaux, UMR CNRS 5295 I2M, Talence, France, [3]INRAE, Aix Marseille University, RECOVER, Aix-en-Provence, France

* Correspondence : Eva Quéheille eva.queheille@univ-eiffel.fr

---

*ABSTRACT*

*The end-of-life of buildings is increasingly involved to improve waste management and environmental concern of the construction sector. A Life Cycle Assessment (LCA) model is suggested in this paper to holistically estimate environmental impacts of the end-of-life of any building. The model allows to consider on site works (i.e. machines, workers…), 40 waste types and 7 waste treatments, with potential benefits from recovery. The model, which is parametric, can be easily instantiated for any building and for different end-of-life strategies (e.g. demolition or deconstruction, reuse or recycling). It can be used as a decision aid by engineers to plan the deconstruction or demolition of a building considering the environmental impact of this process. This model is applied to different real-life cases. The results show that the impacts and therefore the best scenario (i.e. the one that minimizes the environmental impact) are highly case-dependent; for example, deconstruction does not perform better than demolition for all criteria and case studies. This demonstrates the value of a parametric model that can be effective and easily applied to different buildings and strategies.*

*KEY WORDS: Life cycle assessment, Building end-of-life, Demolition waste management, Deconstruction, Recovery.*

---

*Word count: 8,257 words for the manuscript with the tables and references. 10,209 words for the complete document.*

## 1 Introduction

In the coming years, the end-of-life of buildings would become a great environmental concern, as deconstruction, before renovation or a new construction, should increase in order to reduce the energy consumption of buildings and the loss of land. Nevertheless, deconstruction and renovation processes and the resulting waste management also generate environmental impacts (pollution, energy consumption…). In the life of a building, most of the waste is produced at its end-of-life. For instance, in France, almost 40 million tons of waste are produced per year from deconstruction and renovation of buildings [1]. To study the environmental impacts of a building's end-of-life and identify the best scenarios for deconstruction and waste management, Life Cycle Assessment (LCA) is a useful method.

However, each building is different in terms of age, materials (and therefore waste), geometries, location (and therefore distances to waste treatment sites)... Furthermore, the waste treatment possibilities depend on the deconstruction approach and so will the environmental impacts. It is therefore impossible to use general laws that would apply to any building or scenario. It would be necessary to carry out an LCA for each building and each scenario. But conducting an LCA is time consuming and difficult.

To address this problem, this paper proposes a parametric and holistic LCA model that allows end-of-life actors (e.g. deconstruction engineers) to study the environmental impacts and prepare the end-of-life of any building. To do so, the model must meet a triple requirement: 1) consider the deconstruction phase, the waste management and the link between the two, 2) be detailed enough to be applied to a wide variety of buildings (considering a wide variety of materials) and scenarios (demolition, deconstruction, use of machinery, etc.), 3) be easily instantiated to any new case thanks to a set of parameters to be evaluated.

Section 2 presents a review of the literature on LCA studies and models for deconstruction and waste management; it highlights the shortcomings of existing models with respect to our three requirements and the need to provide a new model to solve them. Section 3 presents the proposed model to meet the objectives of the paper. Section 4 presents 5 case studies to analyze the model and its results. Section 5 is devoted to the results and discussion by proposing: 1) to evaluate the ability of the model to study alternative scenarios, with a comparison between deconstruction and demolition, and 2) to deal with different case studies to demonstrate the ability of the model to study various buildings and situations.

## 2 Literature review

A review of LCA studies was conducted in the deconstruction and waste management sector. It focused on LCA studies for demolition and deconstruction of individual buildings. Then, the review does not consider LCA performed for the management of one single waste (e.g. management of concrete waste) or a region (e.g. assess the deconstruction waste management of a city following the urban renewal). Selected papers are separated in two sets: LCA for a specific case study and LCA for decision support tools.

### 2.1 LCA case studies

The first set collects modelling of a LCA system to assess a specific study case [2]–[16]. Some studies focus only on deconstruction waste management [4], [7], [8], [11], [15], [16], but majority of them assess deconstruction with waste management [2], [3], [5], [6], [9], [10], [12]–[14]. Waste management remains the most important part of these studies, modelling waste transport and treatment. Several interesting results can be found in these studies. Firstly, the deconstruction reduces environmental impacts as long as more waste is recycled [3], [5], [10], [13], [14] and substitution is included in the system. Secondly, recycling metals, even in small quantities, is responsible for most of the avoided impacts [4], [9], [12], [15]. Thirdly, the ranking of the contribution of the LCA system stages leads to several differences and contradictions between the case studies: i) some studies find that waste transport is responsible for the majority of impacts [5]–[7], [10], [11], [13], [14], while others find that waste treatment is the most impactful process [8], [9]; ii) the studies also disagree on the contribution of the deconstruction stage to environmental impacts, some considering it as significant [6], [10], [14] and others not [5], [9].

However, these studies have limitations.

Deconstruction is generally limited to the energy consumption of deconstruction machines. Only one study [2] describes deconstruction using explosives (a method that is nowadays little used for safety reasons). Only two studies [9], [14] add dust emission during deconstruction, but none of them include transport of machines, workers commuting or use of other products such as gravels to fill a basement or level the field at the end of the building's deconstruction.

The accuracy of the waste types list is disparate. Some studies focus only on the most common waste, such as structure products (here, as the review is predominant with European studies, the largest structure products are concrete, brick and tiles), steel and wood [2], [5], [10], [11], [15] and the remaining waste is considered as miscellaneous. The other studies detail this miscellaneous fraction, by naming several types of metals other than steel, such as aluminum or copper [6], [9], [14]. New types of waste can also be identified (e.g. glass, gypsum, plastic) and some studies go up to 20 waste types [6], [14], still depending on building considered in the study case.

Waste treatments are generally limited to the most common alternatives, such as recycling or landfill. Only two studies include sorting plants [6], [14], while deconstruction companies can increasingly exploit these sites to save time on site, and only one study considers wood incineration [16].

These limitations bring difficulty to generalize results or to reuse the LCA system for another case and adaptation may be necessary, e.g. by adding other waste types (e.g. furniture), other waste treatments (e.g. backfilling) or specific products used for the works.

## 2.2 Deconstruction and end-of-life models

The second set of references includes decision support tools with LCA [17]–[20]. The tools provided by [17], [18] are used in the design stage of a building project to estimate the end-of-life impacts. They allow to assess design alternatives and minimize the impacts. One model [20] helps to compare several strategies for construction and deconstruction waste at a city scale, while another model [19] is specifically aimed at the deconstruction of an individual building. In each of these tools, LCA is included as a model, which suggests easier reproducibility of calculations for other cases. Several models [17]–[19] use Building Information Modelling (BIM) to precisely provide the LCA model with waste amounts from buildings.

Nevertheless, these tools share some limitations with the first set.

Deconstruction is rarely represented. Impacts from deconstruction are not assessed in [17], [18], [20] while [19] focuses only on energy consumption of machines.

The list of waste type is also disparate. One model [20] focuses only on mineral waste while another [18] adds metals and glass. Two models [17], [19] have the most detailed list of this literature review, up to 15 waste types, including plastics and wood.

Waste treatments are limited to recycling or landfill. Moreover, for design tools such as [17], [18], the treatments selection is applied according to the most common practices in the authors' country. These tools do not allow for the evaluation of multiple waste management strategies. In this objective, one model [19] seems to be the most interesting. The assessment, however, would be limited from an environmental point of view, as this model only calculates carbon emissions. Moreover, BIM are currently rare in the deconstruction sector. Indeed, France is expected to require BIM for building construction by 2022, and the United Kingdom has stipulated the mandatory use of BIM in the public sector since 2016. It will take decades for a building to be deconstructed to provide BIM, which would indeed be effective for waste quantification [21]. In the short-term, to supply the LCA model with waste amounts, a waste audit prior to deconstruction should be carried out by the deconstruction company, using for example tools such as those reviewed by [22], [23]. Using waste rates per $m^2$ floor area is not recommended, as the heterogeneity of construction activities (i.e. date of construction and type of the building) influences the waste generation [24].

The hereby developed LCA model described in this paper resolves the main three drawbacks identified by the previous review, concerning deconstruction process, waste types and waste treatments. The review shows that studies do not agree on the ranking of the end-of-life stages on environmental impacts, especially for deconstruction stage. Then, deconstruction is to be included and detailed with energy consumption of deconstruction machines, machines transport, workers commuting and products use. Waste types and treatments require also a finer modelling, firstly to include the smallest quantities which can provide significant impact and secondly to comply with all the cases which a deconstruction stakeholder may encounter.

## 3 Method and model

### 3.1 Goal and scope definition

The system (Figure 1) is based on stages C (building's end of life) and D (benefits and loads beyond the system boundaries) of the standard EN 15804 [25]:

- Stage C: C1 for Deconstruction/Demolition, C2 for Transport, C3 for Waste processing for recovery, and C4 for waste disposal. Asbestos removal before deconstruction is complex, then not included in our model. The model includes 40 types of waste and 7 types of treatment: reuse, recycling, backfilling, compost (biowaste), sorting, incineration and landfill. C1 step is modeled for 1 m$^2$ of net area, while the other steps are modeled for 1 ton of managed waste.
- Stage D defines the potential environmental benefits from waste recovery. The reference flow is "1 ton of managed waste".

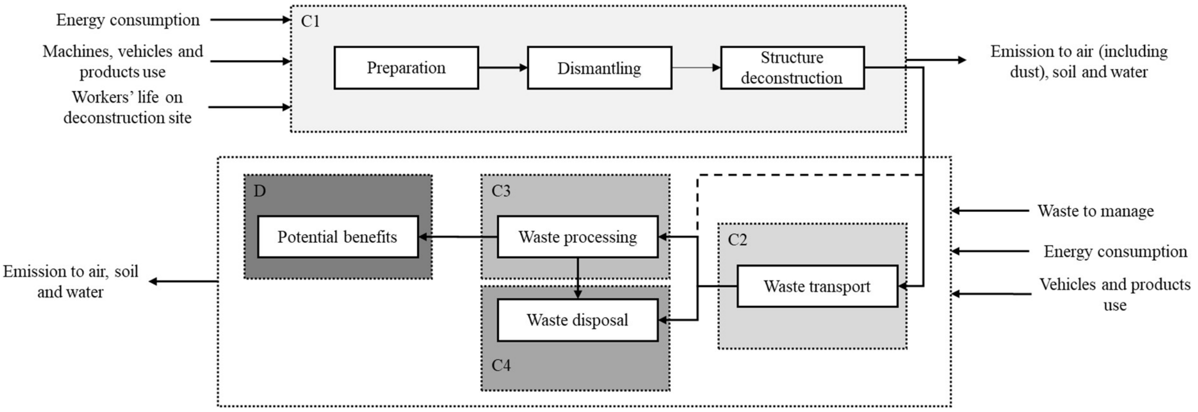

*Figure 1 : LCA system for a building deconstruction*

The LCA model is developed with OpenLCA software and Ecoinvent 3.3 cut-off database [26], [27]. The model is based on typical deconstruction/demolition and waste management practices in France, but it can properly fit with the European context, since the construction model and waste management laws are globally shared around Europe. When data were still missing from European or national surveys, it was obtained from the partnership with a French deconstruction company (BDS).

### 3.2 Deconstruction/Demolition (C1)

Deconstruction begins with preparation (bring fences, power and equipment supplies). Then, dismantling removes elements from the interior of the building. Manual tools (e.g. hammer, crowbar, jackhammer…) and/or small machines (e.g. mini-excavator) are used. Workers sort waste into different containers. Then, deconstruction of the building structure is carried out using excavators. Dust may be emitted. Demolition is similar to deconstruction, without dismantling. Excavators must deal with the interior and the building structure in the same time. Mixed waste is mainly obtained at the end of demolition, as sorting is less precise.

Energy consumption of equipment (e.g. machines) is modeled with two energy sources: diesel or grid electricity. Consumption is calculated for each machine by multiplying the duration of use (days) by the daily consumption. Daily consumption data was provided by the deconstruction company BDS.

Machines production is modeled with the Ecoinvent process "Market for building machine". Its value is obtained by multiplying the number of machines by the ratio between days on site and life expectancy. Life expectancy of machines is assumed to be 5 years, according to BDS. Tools are modelled as 320 kg of the Ecoinvent process "section bar rolling, steel". As with machines production, the value is multiplied by the ratio between days on site and life expectancy (3 years according to BDS). The mass (320 kg) represents the sum of common tools that can be used on a deconstruction site. A sensitivity analysis shows the slights effects of this process, so we retain this value.

Equipment is transported to the deconstruction site by lorries. In the process "transport, freight, lorry16-32 metric ton", we include empty transport, when the lorry returns after delivery [3], and the composition of the French fleet according to the EURO standards [28]. The mass of each equipment is considered, as well as the distance between the deconstruction site and the company.

Containers are modelled with the Ecoinvent processes "intermodal shipping container". 12 to 30 $m^3$ containers are associated with 20-foot shipping containers, and 60 $m^3$ containers with 40-foot shipping containers. However, unlike shipping containers, waste containers rarely have a cover plate. The Ecoinvent processes are adapted with a correction ratio: difference in steel surface area (e.g. a 12 $m^3$ waste container represents 67% of the steel of a 20-foot shipping container). Life expectancy of containers is assumed to be 10 years, according to BDS. Through the study of several BDS deconstruction works, we estimate an average time for a container to be filled with waste by workers, before removal by lorries. For example, a 12 $m^3$ waste container remains on site for 1 day before removal. Containers removal is linked to waste transport (stage C2).

Daily commuting and food of workers are modelled. Each worker is assumed to travel alone with his own car. The Ecoinvent process "transport, passenger car, medium size" is adapted to the French car fleet [29]. Another study of BDS works estimates an average daily commuting distance of 20 km if the deconstruction site is located in the city center (26 km if in the suburbs). One plastic water bottle is consumed per worker each workday, assuming that 2.5 liters are drunk by an adult in a day [30]. The process "polyethylene terephthalate, granulate, bottle grade" models the plastic bottle and the process "tap water" is assumed for water inside the bottle. Lunch is assumed to be ready-made meals. There is a risk that packaging is disposed of in nature, however no statistics were found. A sensitivity analysis on the percentage of packaging disposed of in nature shows a very low contribution in the system, even for 100%. This issue is not included in the model.

The process "Market for gravel, crushed – CH" models gravel for land leveling after deconstruction. The average supply distance is 33 km according to [31].

PM10 dust (particles which size is under 10 µm) production at 200 µg per $m^2$ ("Particulates, > 2.5 um and < 10 um") is based on a dust survey at a demolition site [32].

## 3.3 Waste transport (C2)

Waste removal (i.e. transport from the deconstruction site to treatment plants) is modelled like equipment's transport (section 3.2). If a second transport is necessary (e.g. transport to a recovery plant after a sorting plant), average distances can be used, such as 30 km to inert landfills and to recovery plants for inert or non-hazardous waste, 50 km to non-hazardous landfills and 200 km to hazardous landfills [33]. Containers are modelled with the same processes from section 3.2. Some lorries already have containers (e.g. dump truck) and modelling replicates a 20-foot intermodal shipping container process. Freight processes include lorries production. Use days of containers can be estimated with Equation 1.

$$Days_{Containers} = \sum_{x=1}^{x} \frac{Containers_x}{Daily\ transfer\ _x} \qquad \text{(Equation 1)}$$

Where $Days_{Containers}$ is the use days of containers to transfer the total waste, x is the waste type, *Containers* is the number of containers filled with waste x and *Daily transfers$_x$* is the number of containers transferred by a lorry per day, based on the distance to the treatment plant for the waste x.

## 3.4 Waste processing (C3)

The model considers 40 types of waste, including concrete, brick, plaster, plaster brick, wood, furniture, Waste Electrical and Electronic Equipment (WEEE), windows, glass, several metals, several plastics, sandwich panels, asphalt, biowaste, hazardous waste… Several treatments are possible for each type of waste, such as reuse, recycling, backfilling, compost (only for biowaste), sorting, incineration and landfill (Table 1).

It is important to notice that not every treatment is available for every type of waste, because the disposal treatments are mainly restricted by regulation. For example, wood cannot be sent to backfilling, it has to be recycled or incinerated. Recycling of concrete into structural concrete, which is still a research field, is not included.

*Table 1 : Possible waste treatments in the LCA model - * indicates rare or innovative treatments*

| **Treatment** | **Inert waste** | **Non-hazardous waste** | **Hazardous waste** |
|---|---|---|---|
| Reuse | Bricks, concrete, glass, soil, stone | Furniture | - |
| Recycling | Asphalt, concrete | Carpet*, metals, mineral wool*, plaster, plaster brick*, plastic (e.g. PVC), WEEE, windows, wood, wood furniture | Hazardous WEEE |
| Backfilling | Bricks, concrete, glass, soil, stone, miscellaneous | Plaster brick | |
| Composting | - | Biowaste | - |
| Sorting | Asphalt, bricks, concrete, glass, miscellaneous, soil, stone | Biowaste, bituminous sealing, carpet, furniture, metals, mineral wool, miscellaneous, plaster, plaster brick, plastic (e.g. PVC), WEEE, windows, wood | Hazardous WEEE, miscellaneous, treated wood |
| Incineration | - | Biowaste, bituminous sealing, carpet, furniture, metals, mineral wool, miscellaneous, plaster, plaster brick, plastic (e.g. PVC), WEEE, windows, wood | Hazardous WEEE, miscellaneous, treated wood |
| Landfill | Asphalt, bricks, concrete, glass, miscellaneous, soil, stone | Biowaste, bituminous sealing, carpet, furniture, metals, mineral wool, miscellaneous, plaster, plaster brick, plastic (e.g. PVC), WEEE, windows, wood | Hazardous WEEE, miscellaneous, treated wood |

Reuse is for inert waste and furniture. Inert waste should be reused on site to level the ground (dashed line between stages C1 and C3 in Figure 1). The process is based on the concrete recycling process, with the use of crushers, but removing the infrastructure flows (construction and energy consumption of the building) and waste transport (Table C.1 of Appendix C). Reuse of furniture is handled without material processing, outside the deconstruction site. Furniture is mainly made of wood or metal, and is reused or recycled up to 80% when collected by appropriate compagnies [34]. Furniture is then repaired or simply cleaned by professionals before being used again. The activity is assumed to be manual.

The purpose of waste recycling is to obtain secondary material for the production of a new product. When recycling processes are not available in Ecoinvent, we assume that the recycling process is similar to the production process of the equivalent product from virgin materials, and we remove the input of virgin materials (Table C.2 to Table C.7 of Appendix C). This approach is used primarily for metals recycling. Appendix A presents the process choices for waste recycling.

Site backfilling (e.g. backfilling an old quarry) is modelled with the same process as an inert landfill, as waste is dumped into a hole to fill it. Instead of inert landfill, backfilling with waste replaces soil.

To model inert waste sorting, the process of concrete sorting in Europe is chosen. To model non-hazardous waste sorting, several processes exist in the Ecoinvent database with different non-hazardous waste. However, flows and amount flows are equal. The process of paperboard sorting in Europe is chosen. Waste are sorted, then transferred to a recovery or a disposal plant. To quantify the recovered waste, sorting rates are used (Table 2), estimated from a national study [35] and data collected from a sorting site operating with a grapple excavator and manual workers, which is the most common in France [36].

*Table 2 : Recovered waste mass after a non-hazardous sorting site, based on a representative existing site operating with a grapple excavator and manual workers*

| Waste | Recovered mass after a sorting site (%) |
|---|---|
| Biowaste | 0% |
| Ferrous metals | 31% |
| Non ferrous metals | 50% |
| Other plastic | 0% |
| Other windows | 100% |
| Plaster | 0% |
| Polyethylene plastic | 0% |
| PVC | 55% |
| PVC windows | 48% |
| Wood | 52% |

Energy production, as electricity or heat, can be recovered when waste is burned in incineration plants or when methane is recovered from the degradation of biowaste in landfills. The treatment is actually considered as energy recovery if its efficiency is equal or higher than 60%, according to the EN 16970 standard [37]. In deconstruction projects, landfilling trees or plants with methane recovery only achieves this efficiency [38], [39]. Methane recovery produces heat (Heat and power co-generation, biogas, gas engine, heat, central or small-scale, other than natural gas – FR) and electricity (Heat and power co-generation, biogas, gas engine, electricity high voltage – FR). From waste incineration, we include nevertheless the material recovery of slag and some metals. Indeed, in France, 81% of slag is recycled in roads while steel and aluminum can be recovered respectively from incineration plants at 75% and 50% [38].

### 3.5 Waste disposal (C4)

Two waste disposal scenarios are possible: incineration and landfill. Existing processes in Ecoinvent are used for waste incineration. Inert and sanitary landfill processes are adapted to the French context [3].

Waste can be disposed of, directly or after a sorting site. Mass loss during recycling is also included in the model (arrow between stages C3 and C4 in Figure 1). Indeed, a 100% recycling is rare and a small percentage of secondary material is lost and sent to landfills. This loss is the amount of remaining waste after subtracting the amount of recycled waste, obtained with a recovery rate (from studies [33], [40]–[42] and recycling companies), from the amount of waste transferred to the recycling plant.

### 3.6 Potential benefits from waste recovery (D)

With waste recovery, LCA models usually assume that raw material production is avoided by substitution through the use of secondary material [43]. To facilitate the model, this assumption is set at a 1:1 substitution rate and each recovered waste avoids a specific raw material (Appendix B). For example, steel recycling avoids the production of pig iron, which means that it avoids extraction of iron and its transformation into steel. Concrete recycling avoids gravel production and wood recycling avoids particle board production. For complex wastes such as WEEE or sandwich panels, only the recoverable materials can produce environmental benefits. For example, WEEE recycling is assumed to avoid pig iron and copper production (respectively 48% and 8% of a WEEE mass), while the plastic components cannot be sorted and recycled [44]. Inert reuse on site or site backfilling is supposed to avoid use of soil, which nevertheless represents no environmental impact.

Energy benefits from methane recovery is modelled with electricity ("Electricity, high voltage, production mix – FR") and heat from 3 different processes, which are gas ("Heat production, natural gas, at industrial furnace low-Nox > 100 kW – Europe without Switzerland"), coal ("Heat production, at coal coke industrial furnace 1-10 MW – RoW") and petroleum ("Heat production, light fuel oil, at industrial furnace 1 MW – CH") [41].

## 4 Case studies

### 4.1 Description of the main case study

A large exhibition hall (15,473 m$^2$ net area) has a metal structure and a tent roof with a metal frame. Part of the area includes offices. The hall is to be deconstructed (Table 3). The total human time resource is calculated, instead of the total duration as the sum of the duration for each operation, because the site is large enough to conduct simultaneously dismantling and structure deconstruction while ensuring safety. The demolition scenario is extrapolated. Without dismantling, hydraulic excavators would be the only machines on site and would work longer to process the entire building. Nevertheless, excavators are faster than manual workers. Managing the interior of the building would take 11 days for 2 excavators, which leads to a total reduction of 29% for the human time resource. 18,675 liters of fuel would be used, which is 13% more than with deconstruction.

*Table 3 : Characteristics for deconstruction and demolition of an exhibition hall*

| | **Operation** | **Duration (days)** | **Human resources (nb employees)** | **Human time resource (employee.day)** | **Mechanical resources** | **Energy consumption by machines (liters)** |
|---|---|---|---|---|---|---|
| **Deconstruction scenario** | Preparation | 2 | 2 | 4 | - | - |
| | Dismantling | 29 | 8 | 224 | 2 mini-excavators (1 for 12 days, 1 for 4 days), 2 hydraulic manlift (1 for 1 day, 1 for 3 days), 1 loader (3 days), 1 compact loader (11 days) | 554 |
| | Structure deconstruction | 72 | 5 | 360 | 2 hydraulic excavators (2 for 72 days) | 16,512 |
| | **TOTAL** | **-** | **15** | **588** | | **17,066** |
| **Demolition scenario** | Preparation | 2 | 2 | 4 | - | - |
| | Demolition | 83 | 5 | 415 | 2 hydraulic excavators (2 for 83 days) | 18,675 |
| | **TOTAL** | **-** | **7** | **419** | | **18,675** |

The hall contains 10,348 tons of waste. Waste management for the two scenarios is shown in Table 4.

Building concrete contains a metal reinforcement which represents 3% of the mass, according to the Ecoinvent process "treatment of waste reinforced concrete, collection for final disposal". The metal reinforcement is sorted from concrete by crushers, then recycled. Concerning sandwich panels, only metal could be recycled and foam is landfilled. Miscellaneous non-hazardous waste does not contain any recyclable materials, so the sorting site would transfer it to a landfill. Waste transport is 233,713 ton-km, as the distances between the deconstruction site and the treatment sites do not exceed 30 km, with a mean of 21 km.

For the demolition scenario, excavators do not sort waste with the same efficiency. Aluminum, sandwich panels, WEEE and wood would be transferred to a sorting site where a smaller portion of these wastes would be recycled. However, it only reduces the amount of recycled waste by 1%, as these wastes represent small quantities compared to concrete. Waste transport increases to 244,678 ton-km.

*Table 4 : Waste management for deconstruction and demolition of an exhibition hall*

| Waste type | Amount (tons) | Amount (mass %) | Deconstruction scenario | Demolition scenario |
|---|---|---|---|---|
| Aluminium | 4.4 | 0.04 | Recycling (7% loss) | Sorting site, then 14% recycling |
| Asphalt | 535.7 | 5.18 | Recycling (4% loss) | Recycling (4% loss) |
| Concrete | 9,185.8 | 88.80 | Recycling (4% loss) | Recycling (4% loss) |
| Miscellaneous inert | 35.3 | 0.34 | Landfill | Landfill |
| Miscellaneous non-hazardous | 295.2 | 2.85 | Sorting site, then 100% landfill | Sorting site, then 100% landfill |
| Sandwich panels | 50.2 | 0.45 | Recycling of steel (with 10% loss) and landfill for foam | Sorting site, then 22% recycling (from steel) |
| Steel | 222.2 | 2.15 | Recycling (10% loss) | Recycling (10% loss) |
| WEEE | 0.2 | 0.001 | Recycling (38% loss) | Sorting site, then 100% landfill |
| Wood | 18.8 | 0.18 | Recycling (28% loss) | Sorting site, then 37% recycling |
| **Total** | **10,347.8** | **100** | | |

## 4.2 Description of four various case studies

Table 5 presents four cases with a wide variety in building type and waste amounts.

*Table 5 : Characteristics of four building end-of-life cases – waste is sorted in an amount decreasing order*

| **Case** | 2 | 3 | 4 | 5 |
|---|---|---|---|---|
| **Building** | Apartment building | Hospital | Apartment building | Service sector building |
| **Work** | Complete deconstruction | Complete deconstruction | Partial deconstruction before renovation | Partial deconstruction before renovation |
| **Net area (m$^2$)** | 3,936 | 3,265 | 1,400 | 1,540 |
| **Duration (days)** | 44 | 91 | 27 | 29 |
| **Energy consumption by machines (liters)** | 3,224 | 7,966 | 1,680 | 678 |
| **Inert waste (tons)** | 6672.74 concrete, 26.08 miscellaneous | 1,718.7 concrete, 47.28 miscellaneous | 332.64 concrete, 134.1 miscellaneous | 335.9 concrete, 34.34 miscellaneous |
| **Non hazardous and non inert waste (tons)** | 226.24 miscellaneous, 20.74 plaster, 13.08 steel | 127.26 miscellaneous, 45.56 steel, 4.22 wood, 0.736 copper, 0.54 cables, 0.46 zinc | 61.62 plaster bricks, 31.46 plaster, 25.48 miscellaneous, 3.34 steel | 107.16 miscellaneous, 99.36 plaster bricks, 50 plaster, 33.72 steel, 2.74 copper, 0.56 aluminum, 0.22 cables |
| **Hazardous waste (tons)** | 0.00 | 0.20 (miscellaneous) | 0.00 | 0.00 |
| **Total waste (tons)** | 6,958.88 | 1,944.96 | 588.64 | 664.00 |
| **Waste transport (ton-km)** | 126,005 | 59,078 | 22,745 | 34,310 |
| **Recovery rate (%)** | 93 | 88 | 78 | 78 |
| **Input materials (tons)** | 615.34 (gravels to level the field) | - | - | - |

# 5 Results and discussion

## 5.1 Comparison of scenarios with the main case study

The environmental impacts of the main case study (section 4.1) are calculated with the ILCD 2011 Midpoint+ method for deconstruction and demolition scenarios (Table 6 and Table 7). Demolition is more impactful than deconstruction for twelve environmental impacts, with an increase mean of 35% and an increase maximum of 112% for freshwater eutrophication. The four remaining impacts decrease: freshwater ecotoxicity (-32%), human toxicity through carcinogenic and non-carcinogenic effects (-4% and -2%), and resource depletion (-96%). Indeed, demolition has lower impacts for some indicators in stage C1, and for all indicators in stage C3. However, the improvements are generally offset by a decrease in environmental benefits at stage D. Figure 2, which illustrates the contribution of C-D stages to environmental impacts, allows for further analysis. The contributions for the demolition scenario are identical. The end-of-life stages contribute, from the highest to the lowest, with C3 (Waste processing), C4 (Waste disposal), C2 (Waste transport), then C1 (Deconstruction/Demolition). On the other hand, stage D has large benefits for half of the impacts, which may offset the increase of other stages.

*Table 6 : Environmental impacts for deconstruction of an exhibition hall – grey cells indicate an improvement of demolition compared to deconstruction (correlated with Table 7)*

| **Environmental impact** | **Total** | **C1-Deconstruction** | **C2-Waste transport** | **C3-Waste processing** | **C4-Waste disposal** | **D-Benefits** |
|---|---|---|---|---|---|---|
| 1-Acidification (mole $H^+$ eq) | -398 | 681 | 506 | 1,287 | 70 | -2,942 |
| 2-Climate change (kg $CO_2$ eq) | 2.43E+05 | 7.23E+04 | 2.37E+05 | 1.99E+05 | 2.46E+05 | -5.12E+05 |
| 3-Freshwater ecotoxicity (CTUe) | 9.90E+07 | 4.11E+05 | 4.72E+05 | 6.22E+07 | 3.86E+07 | -2.72E+06 |
| 4-Freshwater eutrophication (kg P eq) | -7.36 | 6.01 | 6.43 | 164.85 | 4.84 | -189.49 |
| 5-Human toxicity, cancer effects (CTUh) | 1.444 | 0.003 | 0.002 | 1.470 | 0.008 | -0.039 |
| 6-Human toxicity, non-cancer effects (CTUh) | 1.820 | 0.008 | 0.029 | 1.379 | 0.521 | -0.117 |
| 7-Ionizing radiation E, interim (CTUe) | 0.296 | 0.033 | 0.110 | 0.343 | 0.010 | -0.200 |
| 8-Ionizing radiation HH (kBq U235 eq) | 9.79E+04 | 5.35E+03 | 1.69E+04 | 1.24E+05 | 2.49E+03 | -5.09E+04 |
| 9-Land use (kg C deficit) | -1.57E+06 | 2.09E+05 | 6.41E+05 | 2.07E+05 | 1.60E+05 | -2.78E+06 |
| 10-Marine eutrophication (kg N eq) | 725 | 280 | 77 | 247 | 627 | -507 |
| 11-Mineral, fossil & ren. resource depletion (kg Sb eq) | 46.74 | 5.43 | 3.00 | 65.29 | 0.34 | -27.32 |
| 12-Ozone depletion (kg CFC-11 eq) | 0.033 | 0.013 | 0.044 | 0.032 | 0.002 | -0.058 |
| 13-Particulate matter (kg PM2.5 eq) | -130.79 | 84.62 | 68.04 | 212.00 | 6.96 | -502.41 |
| 14-Photochemical ozone formation (kg NMVOC eq) | -484 | 825 | 312 | 666 | 137 | -2,424 |
| 15-Terrestrial eutrophication (mole N eq) | 936 | 3,046 | 834 | 2,451 | 226 | -5,622 |
| 16-Water resource depletion ($m^3$ water eq) | 2,022 | 138 | 219 | 5,125 | 59 | -3,518 |

*Table 7 : Environmental impacts for demolition of an exhibition hall – grey cells indicate an improvement of demolition compared to deconstruction (correlated with Table 6)*

| **Environmental impact** | **Total** | **C1-Demolition** | **C2-Waste transport** | **C3-Waste processing** | **C4-Waste disposal** | **D-Benefits** |
|---|---|---|---|---|---|---|
| 1-Acidification (mole $H^+$ eq) | -82.9 | 720 | 530 | 1,209 | 72 | -2,614 |
| 2-Climate change (kg $CO_2$ eq) | 3.07E+05 | 7.42E+04 | 2.48E+05 | 1.87E+05 | 2.59E+05 | -4.62E+05 |
| 3-Freshwater ecotoxicity (CTUe) | 6.72E+07 | 3.42E+05 | 4.93E+05 | 2.74E+07 | 4.09E+07 | -2.01E+06 |
| 4-Freshwater eutrophication (kg P eq) | 8.27 | 5.34 | 6.73 | 155.45 | 5.06 | -164.32 |
| 5-Human toxicity, cancer effects (CTUh) | 1.39 | 0.003 | 0.002 | 1.397 | 0.008 | -0.026 |
| 6-Human toxicity, non-cancer effects (CTUh) | 1.79 | 0.007 | 0.031 | 1.303 | 0.552 | -0.101 |
| 7-Ionizing radiation E, interim (CTUe) | 0.321 | 0.034 | 0.116 | 0.335 | 0.010 | -0.174 |
| 8-Ionizing radiation HH (kBq U235 eq) | 1.04E+05 | 5.40E+03 | 1.77E+04 | 1.21E+05 | 2.62E+03 | -4.24E+04 |
| 9-Land use (kg C deficit) | -1.49E+06 | 2.09E+05 | 6.72E+05 | 1.97E+05 | 1.65E+05 | -2.74E+06 |
| 10-Marine eutrophication (kg N eq) | 818 | 300 | 81 | 235 | 665 | -463 |
| 11-Mineral, fossil & ren. resource depletion (kg Sb eq) | -1.75 | 2.97 | 3.11 | 17.96 | 0.36 | -26.19 |
| 12-Ozone depletion (kg CFC-11 eq) | 0.0381 | 0.013 | 0.046 | 0.030 | 0.002 | -0.054 |
| 13-Particulate matter (kg PM2.5 eq) | -84.4 | 89.22 | 71.22 | 204.97 | 7.23 | -457.02 |
| 14-Photochemical ozone formation (kg NMVOC eq) | -258 | 886 | 327 | 632 | 144 | -2,247 |
| 15-Terrestrial eutrophication (mole N eq) | 1,530 | 3,270 | 873 | 2,325 | 233 | -5,168 |
| 16-Water resource depletion ($m^3$ water eq) | 2,173 | 126 | 229 | 4,894 | 61 | -3,137 |

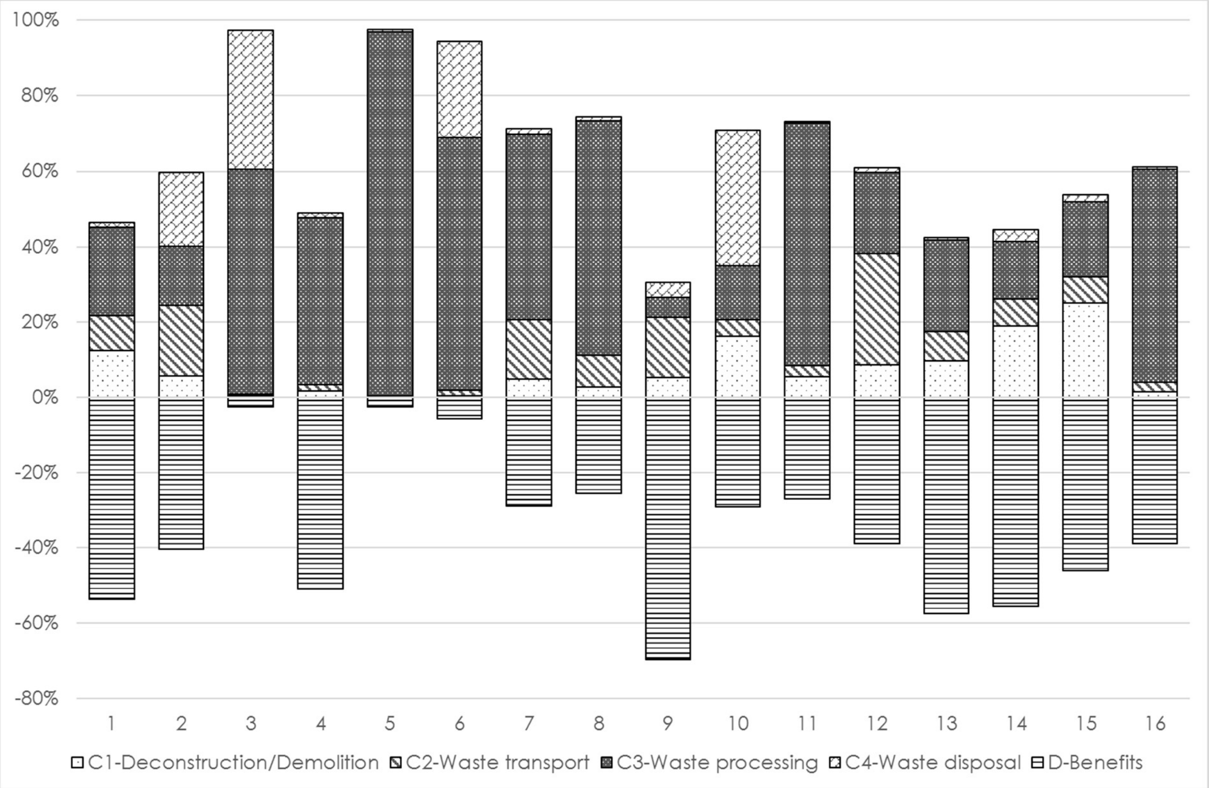

*Figure 2 : Contribution of building end-of-life stages on environmental impacts for deconstruction of an exhibition hall – the impacts numbering is in Table 6*

The demolition scenario clearly affects stage C1. Figure 3 shows the processes contribution on the three largest decreases (impacts #3, 6 and 11 with respectively -7%, -7% and -45%) and the largest increase (impact #14 with +7%) for stage C1. In the deconstruction scenario, workers commuting accounts for up to 70% of the impacts, i.e. up to 20% from dismantling workers and up to 50% from structure workers. Cancelling dismantling is the main cause of decrease, particularly by avoiding workers commuting and the use containers for 29 days. It offsets the impacts increase from structure demolition, because of the duration extension, with workers commuting and fuel consumption (Table 3). However, for photochemical ozone formation (impact #14), the extension of the structure demolition stage exceeds the cancellation of dismantling and compensation is not possible, resulting in a global increase. The same pattern applies to the other impacts. Nevertheless, as shown with Figure 2, stage C1 has a small impact on the overall results.

Stage C2 increases in each impact. Non-hazardous waste transport increases with demolition. Without dismantling, non-hazardous waste is mainly collected to be transferred to sorting sites. Due to the inefficiency of these sites, much of waste is expected to be transferred to landfills.

The decrease in waste recovery affects stage C3, whose impacts decreases. This is quite small (between -3 and -6%) for most of the indicators, but it is stronger for freshwater ecotoxicity (impact #3, with -56%) and resource depletion (impact #11 with -73%). Since stage C3 is the largest contributor in this case (Figure 2), it leads to a decrease for impacts #3, 5, 6, 11. Steel recycling is the largest contributor for these indicators, ahead of aluminum recycling and other waste processing (Figure 4). The small total decrease in impacts #5 and 6 corresponds to the small decrease in stage C3 and a decrease in the amount of recycled steel. In the exhibition hall, most of steel is inherent in the building structure and sorting for recycling is possible even in the case of demolition. Steel from sandwich panels and WEEE (which account for 5% of recyclable steel) cannot be sorted on site and only a small portion is recovered after a sorting site. This pattern applies to other impacts where a small decrease of 5-6% is observed for stage C3. For freshwater ecotoxicity (impact #3) and resource depletion (impact #11), exceptional decreases (-56% and -73%) are related to aluminum, which is barely recycled with demolition scenario. Indeed, aluminum recycling requires a greater amount of energy. It produces more impacts than it avoids for impacts #3 and #11. Concrete and asphalt recycling contributes lowly (Figure 4) despite its large quantity. This process is more present (contribution around 50%) in Ionizing radiation E and HH (impacts #7 and #8), which explains the smallest impact decreases (less than 3%). Non-hazardous sorting, WEEE and wood recycling are marginal processes compared to metal processes, regardless of the impact.

Stage C4 impacts increase due to more landfilling.

With the decrease of waste recovery, stage D offers less benefits, losing up to 34% for human toxicity by cancer effects (impact #5). Figure 5 shows that the processes contribution is more distributed than in stage C3. Benefits from concrete and asphalt recycling are more present. Copper and particle board production, from WEEE and wood recycling are the lowest contributors. Once again, restriction of aluminum recycling is mainly responsible for the differences with the alternative scenario.

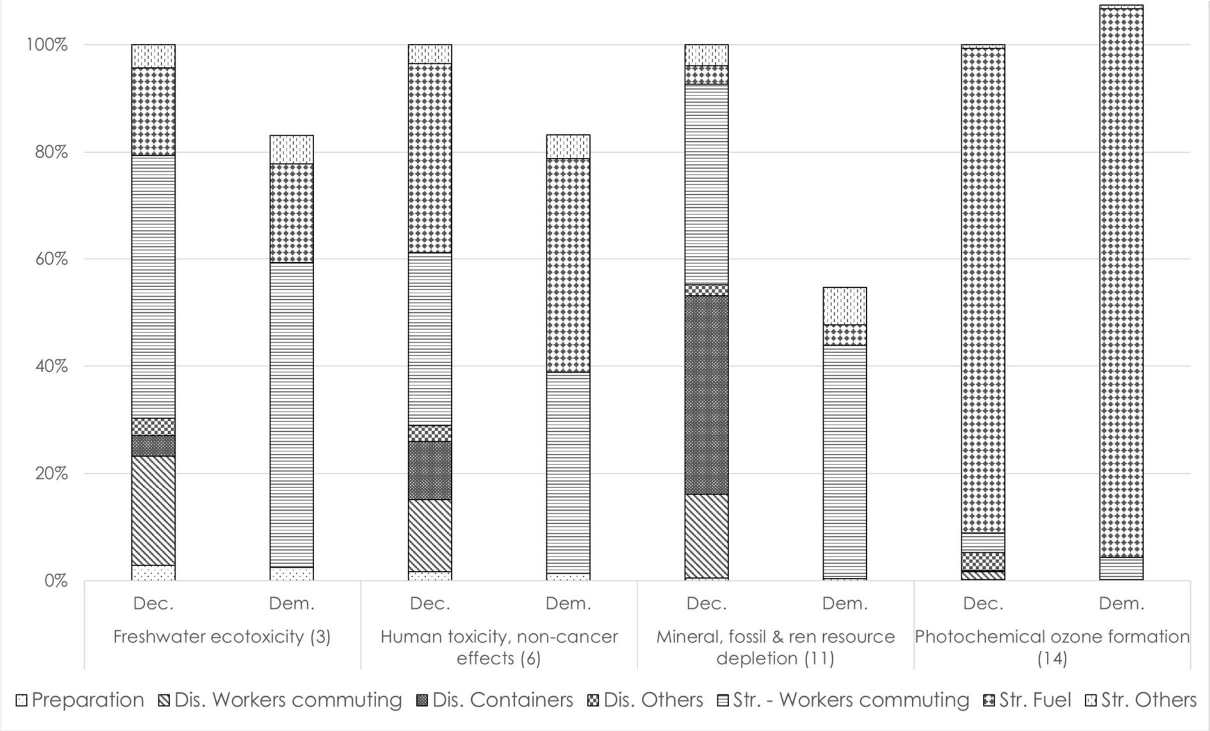

*Figure 3 : Process contribution on several environmental impacts of stage C1 (Dis. for dismantling and Str. for structure demolition) for an exhibition hall deconstruction (Dec.) and the demolition alternative scenario (Dem.)*

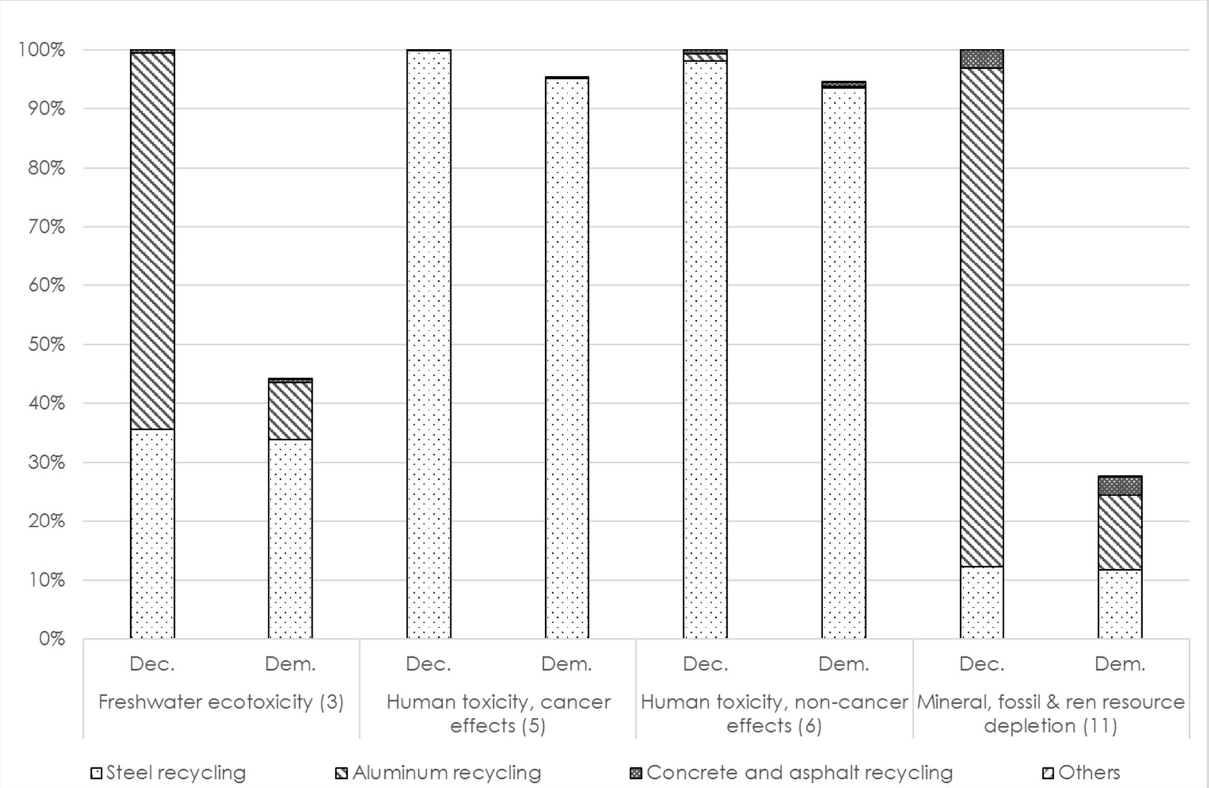

*Figure 4 : Waste type contribution on several environmental impacts of stage C3 for an exhibition hall deconstruction (Dec.) and the demolition alternative scenario (Dem.)*

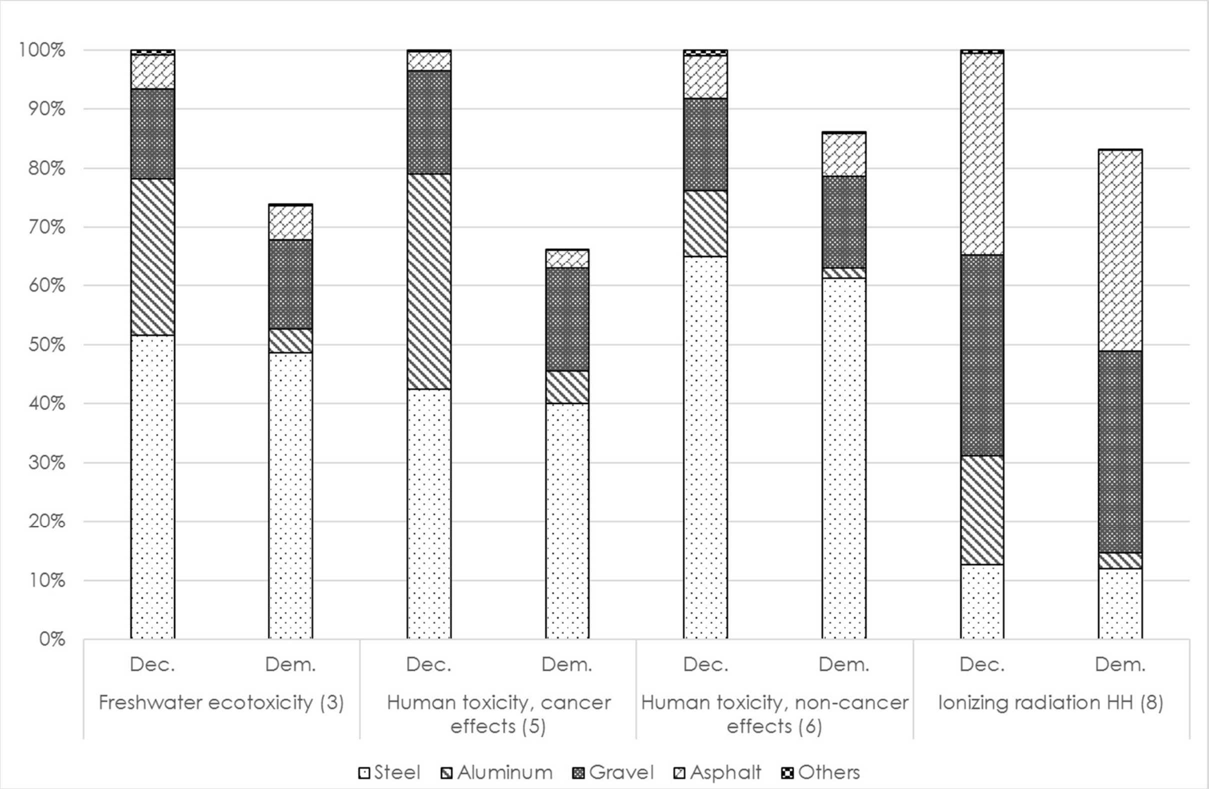

*Figure 5 : Product type contribution on several environmental impacts of stage D for an exhibition hall deconstruction (Dec.) and the demolition alternative scenario (Dem.)*

Other scenarios are performed with the deconstruction strategy. Doubling the waste transport distances increases 13 of the impacts by up to 60% of the total results. Resources changes (use 1 hydraulic excavator instead of two, double then triple the workers for dismantling) increases C1 stage impacts by up to 25%, but have very little effect on the total results. These findings are however inherent to the case. It is conceivable that transport distances would have less impact if there was little waste (i.e. less transport), or hazardous waste (i.e. greater impacts from C3 and C4 stages) and so on. If landfills were far from sorting sites, it would otherwise increase transport impacts. The demolition scenario would also lose its advantages if there was no aluminum in the building, which would avoid the great energy consumption from aluminum recycling.

### 5.2 Evaluation of five various case studies

To assess the model ability to process end-of-life of various buildings, four case studies (section 4.2) are added to the main study. The ILCD 2011 Midpoint+ method is used to calculate impacts of the four cases (Table 8) and the average contribution of stages C1-D is calculated, main case included at the deconstruction scenario, (Figure 6).

*Table 8 : Environmental impacts for four building end-of-life cases*

| Environmental impact | Case 2 | Case 3 | Case 4 | Case 5 |
|---|---|---|---|---|
| Acidification (mole $H^+$ eq) | 1,17E+05 | 242 | 53 | -154 |
| Climate change (kg $CO_2$ eq) | 1,61E+07 | 1,48E+05 | 3,94E+04 | 9,19E+04 |
| Freshwater ecotoxicity (CTUe) | 1,90E+08 | 1,91E+07 | 3,61E+06 | 1,88E+07 |
| Freshwater eutrophication (kg P eq) | 3,894 | -5.59 | 0.60 | -46 |
| Human toxicity, cancer effects (CTUh) | 2.74 | 0.27 | 0.04 | 0.12 |
| Human toxicity, non-cancer effects (CTUh) | 7.65 | 0.42 | 0.07 | 0.2 |
| Ionizing radiation E, interim (CTUe) | 19.22 | 0.10 | 0.02 | 0.03 |
| Ionizing radiation HH (kBq U235 eq) | 5,70E+06 | 2,62E+04 | 3,919 | 6,112 |
| Land use (kg C deficit) | 5,61E+08 | -7,11E+04 | 5,35E+04 | 6,72E+04 |
| Marine eutrophication (kg N eq) | 3,48E+04 | 362 | 68 | 196 |
| Mineral, fossil & ren. resource depletion (kg Sb eq) | 7,017 | -1.30 | 1.34 | 1.95 |
| Ozone depletion (kg CFC-11 eq) | 2.884 | 0.019 | 0.006 | 0.007 |
| Particulate matter (kg PM2.5 eq) | 1,34E+04 | 31 | 14 | -14 |
| Photochemical ozone formation (kg NMVOC eq) | 1,05E+05 | 270 | 56 | -38 |
| Terrestrial eutrophication (mole N eq) | 4,24E+05 | 1,306 | 219 | -84 |
| Water resource depletion ($m^3$ water eq) | 5,66E+05 | 581 | 42 | 144 |

Case 2 presents extremely high impacts compared to the 3 other cases. Here, stage C1 is by far the largest contributor, due to the use of gravels to level the site. Regarding the other cases, the importance of waste management agrees with the main study (section 5.1). A comparison is also possible with the literature studies which assess deconstruction with waste management, as the waste composition of the cases (case 5 excepted) have on average 90% of inert waste, such as [2], [3], [6], [9], [10], [14], [19] where the composition of the study cases is available. Then, the importance of waste management correlates with literature studies [8], [9]. Waste processing is found to be the most important stage, not waste transport as some other studies have found [5]–[7], [10], [11], [13], [14]. Here, the difference with the literature is due to the modelling discrepancies (e.g. accuracy of waste types and treatments). Waste transport and waste disposal are of the same order of contribution overall.

Deconstruction and demolition works (stage C1) have mainly the lowest contribution, as in some studies [5], [9], differently from some others [6], [10], [14]. For case 2, without the gravels, the contribution reaches the same ranking, with waste processing as the largest contributor and deconstruction the smallest.

Comparison of literature studies with LCA results is another possible approach, which is however limited by the need to share the same modelling (deconstruction and waste management), the same calculated environmental impacts and to have raw or comparable results. Excluding the case 2, where the use of gravels greatly affects the results, the cases share similarities with the results of [13], [14]. The climate change impact is 62.5 kg $CO_2$ eq /m$^2$ without the potential benefits of stage D and 37.2 kg $CO_2$ eq /m$^2$ with stage D. It is respectively 15% more than [13] and 10% more than [14]. This slight increase is brought by the greater accuracy of the model. However, the results do not match the case of [19], which emits -487 kg $CO_2$ eq /m$^2$. The modelling methodology and the LCA database are responsible for this case. Indeed, the environmental benefits from waste recovery per ton in [19] are two or three times higher than those in the model.

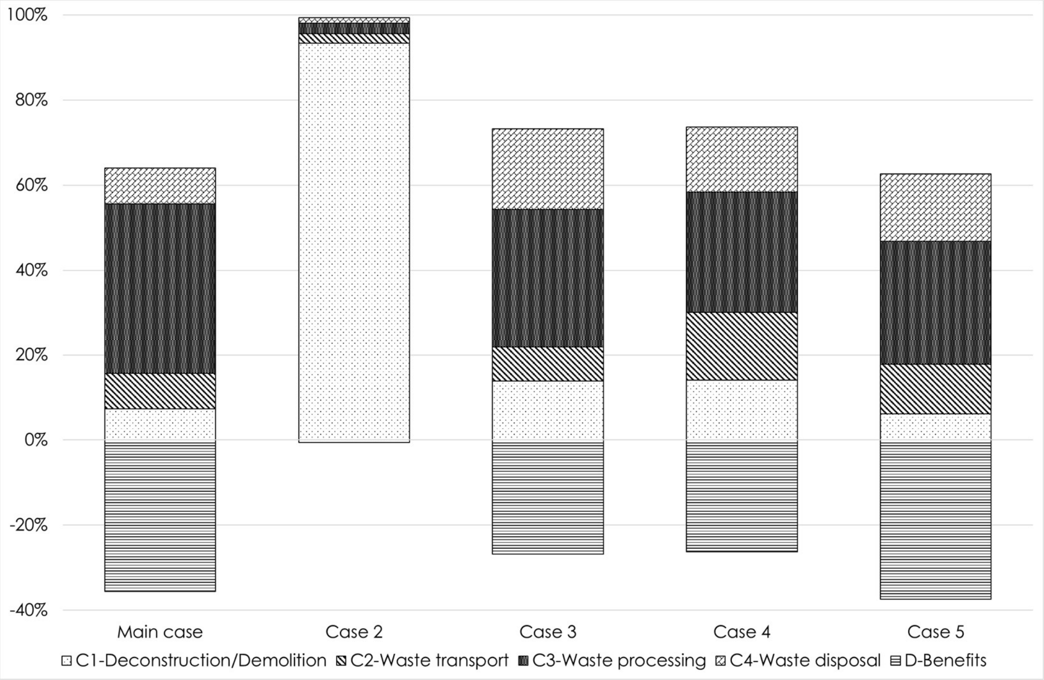

*Figure 6 : Mean contribution of building end-of-life stages on environmental impacts for the five cases*

The use of the LCA model enables to study several cases with the same methodology and, if required, to compare the results efficiently. Metal waste, with the highest recycling benefits per ton, dominate C3 and D stages in the majority of impacts compared to other larger waste amounts. Thus, the characteristics of case 4 are similar to those of case 5, except fewer metals, which is the major cause of lower benefits (D stage) and higher total impacts. Metal waste, even the rarest metals (e.g. copper, zinc), require detailed quantification, but do not always control the total results. Case 3, for example, has a similar ratio of metal waste as the main case and case 5. However, a higher contribution from C1 stage (due to higher energy consumption per net area) and C4 stage (due to landfilling of hazardous waste) prevents acidification and particulate matter to present negative results. On the other hand, case 5 do not meet enough D benefits to show negative results for land use, due to a lower ratio of concrete to recycle.

This comparative study shows the importance of achieving in-depth modelling, from C1 stage which is not to neglect, to the required detail of waste quantification. The LCA model can then be used to aim exhaustive results, either to estimate the future impacts of a deconstruction or to compare several scenarios.

On the other hand, the in-depth modelling strongly affects the manual set-up and calculation time. To ease the use of the model, some simplifications are possible by using broad estimations for small activities (e.g. energy consumption on site by machines if the stakeholder does not wish to study alternative scenarios with this point) and removing marginal impacts, such as site preparation, workers food, tools or containers use on site which, for each of the five cases, rarely contribute more than 1% of the total results.

## 6 Conclusion

In this paper, an LCA model is built with the capacity to study the end-of-life of any building. The model resolves the lacks identified in the existing systems and models of the literature, specifically the difficulty of replicating the calculations on different cases and different scenarios, and the lack of accuracy. Then, the model integrates 40 waste types, 7 waste treatments and considers the impacts from the complete end-of-life, including the demolition/deconstruction approach, waste management and the relation between demolition mode and waste management. The LCA model is based on the French practices, but adaptation is possible to other contexts by modifying the location of Ecoinvent processes in accordance with the target country (assuming that such local processes are available) or by adding waste treatments that are specific to the target country.

An analysis of the model was carried out in two steps. Firstly, the comparison of several alternative strategies on a case study is proven to be feasible. The test (comparing deconstruction and demolition) gives interesting results, as demolition appears to provide less impacts than deconstruction for 4 of the 16 environmental impacts. It shows that the choice of the end-of-life strategy should not focus only on climate change, but include the wider panel of environmental impacts that allows LCA. Secondly, the level of detail and the versatility of the model is assessed through five case studies. Efforts made for in-depth modelling are justified, as the presence of some waste (e.g. aluminum with the main case) or the use of products (e.g. gravels with case 2) can greatly affect results. Stages C3 and D require the most precise care in LCA modelling, as the highest impacts come from waste processing, followed by waste disposal and waste transport, while deconstruction/demolition appears to be the lowest impact provider. The identification of some trends advises to neglect some very low impact aspects of the deconstruction stage, such as workers food, tools and containers use on site. Nevertheless, it is still relevant to keep stage C1; it is the largest contributor for two impacts, the technical comparison between deconstruction and demolition may still provide interesting points to consider (e.g. reduce fuel consumption?) and some specific works (e.g. field levelling) could change results.

With the present model, the comparison of alternatives strategies requires manual handling, which may hinder the deepening of the study due to the time required. To better assist end-of-life stakeholders for decision making, it is planned to continue this work by including the LCA model into a decision support tool, which would automatically find the best strategies according to the environmental impacts and criteria such as cost and delays.

## 7 Acknowledgment

The authors wish to thank the deconstruction company BDS for funding, along with the Nouvelle Aquitaine region (France), this research project.

## 8 References

[1] CGDD, "Entreprises du BTP : 227,5 millions de tonnes de déchets en 2014," *Datalab Essent.*, vol. Mars 2017, no. 96, pp. 1–4, 2017.

[2] G. A. Blengini, "Life cycle of buildings, demolition and recycling potential : A case study in Turin, Italy," *Build. Environ.*, vol. 44, pp. 319–330, 2009, doi: 10.1016/j.buildenv.2008.03.007.

[3] R. Brière, "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, France, 2016.

[4] H. Dahlbo *et al.*, "Construction and demolition waste management - a holistic evaluation of environmental performance," *J. Clean. Prod.*, vol. 107, pp. 333–341, 2015, doi: http://dx.doi.org/10.1016/j.jclepro.2015.02.073.

[5] A. Di Maria, J. Eyckmans, and K. Van Acker, "Downcycling versus recycling of construction and demolition waste : Combining LCA and LCC to support sustainable policy making," *Waste Manag.*, vol. 75, pp. 3–21, 2018, doi: https://doi.org/10.1016/j.wasman.2018.01.028.

[6] A. Mastrucci, A. Marvuglia, E. Popovici, U. Leopold, and E. Benetto, "Geospatial characterization of building material stocks for the lifecycle assessment of end-of-life scenarios at the urban scale," *Resour. Conserv. Recycl.*, vol. 123, pp. 54–66, 2017, doi: http://dx.doi.org/10.1016/j.resconrec.2016.07.003.

[7] C. Mei Mah, T. Fujiwara, and C. Siong Ho, "Environmental impacts of construction and demolition waste management alternatives," *Chem. Eng. Trans.*, vol. 63, pp. 343–348, 2018, doi: 10.3303/CET1863058.

[8] O. Ortiz, J. C. Pasqualino, and F. Castells, "Environmental performance of construction waste: Comparing three scenarios from a case study in Catalonia, Spain," *Waste Manag.*, vol. 30, pp. 646–654, 2010, doi: 10.1016/j.wasman.2009.11.013.

[9] P. Vitale, N. Arena, F. Di Gregorio, and U. Arena, "Life cycle assessment of the end-of-life phase of a residential building," *Waste Manag.*, vol. 60, pp. 311–321, 2017, doi: http://dx.doi.org/10.1016/j.wasman.2016.10.002.

[10] B. Sára, E. Antonini, and M. Tarantini, "Application of Life Cycle Assessment (LCA) methodology for selective demolition and reuse-recycling of building materials and products," pp. 1–5, 2000.

[11] S. Butera, T. H. Christensen, and T. F. Astrup, "Life cycle assessment of construction and demolition waste management," *Waste Manag.*, vol. 44, pp. 196–205, 2015, doi: http://dx.doi.org/10.1016/j.wasman.2015.07.011.

[12] C. K. Chau, J. M. Xu, T. M. Leung, and W. Y. Ng, "Evaluation of the impacts of end-of-life management strategies for deconstruction of a high-rise concrete framed office building," *Appl. Energy*, pp. 1–9, 2016, doi: 10.1016/j.apenergy.2016.01.019.

[13] A. Coelho and J. De Brito, "Influence of construction and demolition waste management on the environmental impact of buildings," *Waste Manag.*, vol. 32, no. 3, pp. 532–541, 2012, doi: https://doi.org/10.1016/j.wasman.2011.11.011.

[14] E. Martínez, Y. Nuñez, and E. Sobaberas, "End of life of buildings : three alternatives, two scenarios. A case study," *Int. J. Life Cycle Assess.*, vol. 18, pp. 1082–1088, 2013, doi: 10.1007/s11367-013-0566-4.

[15] T. Wang, J. Wang, P. Wu, J. Wang, Q. He, and X. Wang, "Estimating the environmental costs and benefits of demolition waste using life cycle assessment and willingness-to-pay: A case study in Shenzhen," *J. Clean. Prod.*, vol. 172, pp. 14–26, 2018, doi: https://doi.org/10.1016/j.jclepro.2017.10.168.

[16] H. Wu, H. Duan, J. Wang, T. Wang, and X. Wang, "Quantification of carbon emission of construction waste by using streamlined LCA: a case study of Shenzhen, China," *J. Mater. Cycles Waste Manag.*, vol. 17, pp. 637–645, 2015, doi: 10.1007/s10163-015-0404-9.

[17] J. Xu, Y. Shi, Y. Xie, and S. Zhao, "A BIM-Based construction and demolition waste information management system for greenhouse gas quantification and reduction," *J. Clean. Prod.*, vol. 229, pp. 308–324, Aug. 2019, doi: 10.1016/j.jclepro.2019.04.158.

[18] S. Su, S. Li, J. Ju, Q. Wang, and Z. Xu, "A building information modeling-based tool for estimating building demolition waste and evaluating its environmental impacts," *Waste Manag.*, vol. 134, pp. 159–169, Oct. 2021, doi: 10.1016/j.wasman.2021.07.025.

[19] J. Wang, H. Wu, H. Duan, G. Zillante, J. Zuo, and H. Yuan, "Combining life cycle assessment and Building Information Modelling to account for carbon emission of building demolition waste: A case study," *J. Clean. Prod.*, vol. 172, pp. 3154–3166, 2018, doi: https://doi.org/10.1016/j.jclepro.2017.11.087.

[20] A. Yazdanbakhsh, "A bi-level environmental impact assessment framework for comparing construction and demolition waste management strategies," *Waste Manag.*, vol. 77, pp. 401–412, Jul. 2018, doi: 10.1016/j.wasman.2018.04.024.

[21] O. Akinade *et al.*, "BIM-Based deconstruction tool : Towards essential functionalities," *Int. J. Sustain. Built Environ.*, vol. 6, pp. 260–271, 2017.

[22] O. O. Akinade *et al.*, "Evaluation criteria for construction waste management tools: towards a holistic BIM framework," *Int. J. Sustain. Build. Technol. Urban Dev.*, vol. 7, no. 1, pp. 3–21, Jan. 2016, doi: 10.1080/2093761X.2016.1152203.

[23] P. Villoria-Sáez, C. Porras-Amores, and M. del Río Merino, "Estimation of construction and demolition waste," in *Advances in Construction and Demolition Waste Recycling*, Elsevier, 2020, pp. 13–30. doi: 10.1016/B978-0-12-819055-5.00002-4.

[24] J.-L. Gálvez-Martos, D. Styles, H. Schoenberger, and B. Zeschmar-Lahl, "Construction and demolition waste best management practice in Europe," *Resour. Conserv. Recycl.*, vol. 136, pp. 166–178, 2018, doi: https://doi.org/10.1016/j.resconrec.2018.04.016.

[25] CEN, *Substainability of construction works. Guidance for the implementation of EN 15804*. 2016, p. 38.

[26] Ecoinvent, *Ecoinvent cut-off*. 2016. [Online]. Available: https://www.ecoinvent.org/

[27] GreenDelta, *OpenLCA*. 2019. [Online]. Available: http://openlca.org

[28] Comité National Routier, *Enquête longue distance 2017*. 2018.

[29] M. André, A.-L. Roche, and L. Bourcier, *Statistiques de parcs et trafic pour le calcul des émissions de polluants des transports routiers en France - Rapport final*. 2014.

[30] European Food Safety Authority, "Scientific Opinion on Dietary Reference Values for water," *EFSA J.*, vol. 8, no. 3, pp. 1–48, 2010, doi: 10.2903/j.efsa.2010.1459.

[31] UNPG and UNICEM, *Situation, enjeux et perspectives du transport et de la distribution des granulats*. 2012.

[32] ADEME, SETEC Energie Environnement, and Bio by Deloitte, *Qualité de l'air et émissions polluantes des chantiers du BTP : Etat des connaissances et mesures d'atténuation dans le bâtiment et les travaux publics en faveur de la qualité de l'air*. 2017.

[33] SEDDRE and Crowe Sustainable Metrics, *Empreinte carbone de la valorisation des déchets du bâtiment en France*. 2019.

[34] ADEME and Deloitte Développement Durable, "Rapport annuel de la filière des Déchets d'Eléments d'Ameublement (DEA)," 2017.

[35] Treize Développement and Pöyry SAS, "Analyse technico-économique de 39 plateformes françaises de tri/valorisation des déchets du BTP," Synthèse réalisée pour l'ADEME, 2011. Accessed: Sep. 30, 2016. [Online]. Available: http://www.ademe.fr/analyse-technico-economique-39-plate-formes-francaises-trivalorisation-dechets-btp

[36] FNADE, *Etat des lieux des centres de tri de déchets non dangereux des activités économiques en France. Données 2010*. ADEME, 2012.

[37] CEN, *Substainability of construction works. Guidance for the implementation of EN 15804*. 2016, p. 38.

[38] A. Beylot, S. Muller, Y. Ménard, P. Michel, and M. Descat, *L'outil WILCI pour l'analyse du cycle de vie de l'incinération des déchets ménagers et assimilés en France*. ADEME, BRGM, SVDU, 2017.

[39] GREENBIRDIE, *Chaleur issue de la méthanisation : de réelles opportunités*. ADEME, 2016.

[40] ADEME, *Recyclage des PVC par la société VEKA à Vendeuvre-sur-Barse (10)*. 2014.

[41] FEDEREC and ADEME, *Évaluation environnementale du recyclage en France selon la méthodologie de l'analyse de cycle de vie*. 2017.

[42] GTM Bâtiment, *Démarche REVALO - Fenêtre en fenêtre - Note de synthèse*. Convention ADEME 1206C0072, 2014.

[43] European Commission, Joint Research Centre, and Institute for Environment and Sustainability, "International Reference Life Cycle Data System (ILCD) Handbook - General guide for Life Cycle Assessment - Detailed guidance," Publications Office of the European Union, First edition EUR 24708 EN, 2010.

[44] ADEME, *Les filières à responsabilité élargie du producteur : Panorama*. ADEME, 2017.

# 9 Appendices

## Appendix A. Process assumptions in Ecoinvent processes for waste recycling

*Table A.1 : Process assumptions for waste recycling - * process assumed equivalent to the production process of primary product without use of virgin materials*

| **Waste** | **Process** |
|---|---|
| Asphalt or concrete | "Gravel production, crushed – CH" * |
| Carpet | "Weaving, bast fibre – RoW" * |
| Glass | "Flat glass production, uncoated – RER " * |
| Metal (aluminium from metal elements, windows) | "Aluminium scrap, prepared for melting – GLO" then "Production of aluminium cast alloy – RER" |
| Metal (cooper from metal elements, electric cables) | "Treatment of used cables – GLO" |
| Metal (steel from metal elements, sandwich panels, windows) | "Sorting and pressing of iron scrap – RER" then "Steel production, electricity, low-alloyed – RER" * |
| Metal (zinc) | "Zinc coating, coils – RER" |
| Plaster | "Treatment of waste gypsum plasterboard, recycling – CH" |
| Plaster brick | "Gravel production, crushed – CH" * and "Treatment of waste gypsum plasterboard, recycling – CH" |
| Polystyrene | "Polystyrene foam slab production – CH" * |
| PVC (from plastic elements, windows) | "Polyvinylchloride, suspension polymerised, production – CH" * |
| WEEE (hazardous or not) | "Treatment of waste electric and electronic equipment, recycling – GLO" |
| Wood (from structure, furniture, windows…) | "Treatment of waste wood, post-consumer, sorting and shredding – CH" |

## Appendix B. Process assumptions in Ecoinvent processes for potential benefits after waste recycling

*Table B.1 : Process assumptions for potential benefits after waste recycling*

| **Waste** | **Process** |
|---|---|
| Asphalt | "Mastic asphalt production – CH" |
| Biowaste | "Single superphosphate production \| phosphate fertiliser, as P2O5 – RER" |
| Carpet | "Nylon production – RER" |
| Concrete | "Gravel production, crushed – CH" |
| Glass | "Flat glass production, uncoated – RER" |
| Metal (aluminum from metal elements, windows) | "Aluminium production, primary liquid, prebake – IAI Area, EU27 & EFTA" |
| Metal (cooper from metal elements, electric cables, WEEE) | "Copper production, blister copper – RER" |
| Metal (steel from metal elements, sandwich panels, windows, WEEE) | "Pig iron production – GLO" |
| Metal (zinc) | "Zinc coating, coils – RER" |
| Plaster | "Gypsum plasterboard production – CH" |
| Plaster brick | "Gravel production, crushed – CH" and "Gypsum plasterboard production – CH" |
| Polystyrene | "Polystyrene foam slab production – RER" |
| PVC (from plastic elements, windows) | "Polyvinylchloride, suspension polymerised, production – CH" |
| Wood (from structure, furniture, windows…) | "Particle board production, for indoor use – RER" |

## Appendix C. Process assumptions details in Ecoinvent processes for waste recovery

*Table C.1 : Model of the process for reuse of 1 kg inert waste, based on the process "Gravel production, crushed – CH" – E: elementary flow, I: Intermediate flow*

| **INPUT FLOWS** | | | | |
|---|---|---|---|---|
| **Name of flow** | **Flow type** | **Unit** | **Value** | **Provenance process** |
| Conveyor belt | I | m | 9.51E-8 | market for conveyor belt – GLO |
| Diesel, burned in building machine | I | MJ | 0.0143 | market for diesel, burned in building machine – GLO |
| Lubricating oil | I | kg | 2.5E-6 | market for lubricating oil – GLO |
| Steel, low-alloyed, hot rolled | I | kg | 5.10E-6 | market for steel, low-alloyed, hot rolled – GLO |
| Synthetic rubber | I | kg | 4.00E-6 | market for synthetic rubber – GLO |
| Waste mineral oil | I | kg | -2.50E-6 | market for waste mineral oil – CH |

| **OUTPUT FLOWS** | | | | |
|---|---|---|---|---|
| **Name of flow** | **Flow type** | **Unit** | **Value** | **Destination process** |
| Particulates, < 2.5 um | E | kg | 4.00E-10 | Emission to air/low population density |
| Particulates, > 10 um | E | kg | 5.60E-9 | Emission to air/low population density |
| Particulates, > 2.5 um, and < 10 um | E | kg | 2.00E-9 | Emission to air/low population density |

*Table C.2 : Model of the process for recycling of 1 kg carpet waste, based on the process "Weaving, bast fibre – RoW" – E: elementary flow, I: Intermediate flow*

| **INPUT FLOWS** | | | | |
|---|---|---|---|---|
| **Name of flow** | **Flow type** | **Unit** | **Value** | **Provenance process** |
| Electricity, high voltage | I | kWh | 0.1337 | market for electricity, low voltage – CH |
| Packaging box factory | I | Item) | 5E-10 | market for packaging box factory – GLO |

| **OUTPUT FLOWS** | | | | |
|---|---|---|---|---|
| **Name of flow** | **Flow type** | **Unit** | **Value** | **Destination process** |
| None | | | | |

*Table C.3 : Model of the process for recycling of 1 kg polyvinylchloride waste, based on the process "Polyvinylchloride, suspension polymerised, production – CH" – E: elementary flow, I: Intermediate flow*

| **INPUT FLOWS** | | | | |
|---|---|---|---|---|
| **Name of flow** | **Flow type** | **Unit** | **Value** | **Provenance process** |
| Electricity, low voltage | I | kWh | 0.30869 | market for electricity, low voltage – CH |
| Heat, district or industrial, natural gas | I | MJ | 8.22624 | market for heat, district or industrial, natural gas – CH |
| Water, decarbonized, at user | I | kg | 0.00014 | market for water, decarbonized, at user – GLO |

| **OUTPUT FLOWS** | | | | |
|---|---|---|---|---|
| **Name of flow** | **Flow type** | **Unit** | **Value** | **Destination process** |
| Water | E | kg | 5.27E-5 | Emission to air/unspecified |
| Water | E | $m^3$ | 8.33E-8 | Emission to water/unspecified |

*Table C.4 : Model of the process for recycling of 1 kg concrete or asphalt waste, based on the process "Gravel production, crushed – CH" – E: elementary flow, I: Intermediate flow*

| **INPUT FLOWS** | | | | |
|---|---|---|---|---|
| **Name** | **Type** | **Unit** | **Value** | **Provenance process** |
| Conveyor belt | I | m | 9.51E-8 | market for conveyor belt – GLO |
| Diesel, burned in building machine | I | MJ | 0.0143 | market for diesel, burned in building machine – GLO |
| Electricity, medium voltage | I | kWh | 0.01327 | market for electricity, medium voltage – GLO |
| Gravel/sand quarry infrastructure | I | Item | 4.75E-11 | market for gravel/sand quarry infrastructure – GLO |
| Heat, central or small-scale, other than natural gas | I | MJ | 0.00164 | market for heat, central or small-scale, other than natural gas – CH |
| Lubricating oil | I | kg | 2.5E-6 | market for lubricating oil – GLO |
| Steel, low-alloyed, hot rolled | I | kg | 5.10E-6 | market for steel, low-alloyed, hot rolled – GLO |
| Synthetic rubber | I | kg | 4.00E-6 | market for synthetic rubber – GLO |
| Waste mineral oil | I | kg | -2.50E-6 | market for waste mineral oil – CH |
| **OUTPUT FLOWS** | | | | |
| **Name** | **Type** | **Unit** | **Value** | **Destination process** |
| Particulates, < 2.5 um | E | kg | 4.00E-10 | Emission to air/low population density |
| Particulates, > 10 um | E | kg | 5.60E-9 | Emission to air/low population density |
| Particulates, > 2.5 um, and < 10 um | E | kg | 2.00E-9 | Emission to air/low population density |

*Table C.5 : Model of the process for recycling of 1 kg polystyrene waste, based on the process "Polystyrene foam slab production – CH" – E: elementary flow, I: Intermediate flow*

| **INPUT FLOWS** | | | | |
|---|---|---|---|---|
| **Name** | **Type** | **Unit** | **Value** | **Provenance process** |
| Electricity, low voltage | I | kWh | 0.30869 | market for electricity, low voltage – CH |
| Heat, district or industrial, natural gas | I | MJ | 8.22624 | market for heat, district or industrial, natural gas – CH |
| Polystyrene scrap, post-consumer | I | kg | 1 | market for polystyrene scrap, post-consumer – GLO |
| Water, decarbonized, at user | I | kg | 0.00014 | market for water, decarbonized, at user – GLO |
| **OUTPUT FLOWS** | | | | |
| **Name** | **Type** | **Unit** | **Value** | **Destination process** |
| Water | E | kg | 5.27E-5 | Emission to air/unspecified |
| Water | E | $m^3$ | 8.33E-8 | Emission to water/unspecified |

*Table C.6 : Model of the process for recycling of 1 kg glass waste, based on the process "Flat glass production, uncoated – RER" – E: elementary flow, I: Intermediate flow*

| **INPUT FLOWS** | | | | |
|---|---|---|---|---|
| **Name** | **Type** | **Unit** | **Value** | **Provenance process** |
| Electricity, medium voltage | I | kWh | 0.111 | market group for electricity, medium voltage – RER |
| Flat glass factory | I | Item | 2.41E-10 | market for flat glass factory – GLO |
| Heavy fuel oil | I | kg | 0.0738 | market group for heavy fuel oil – RER |
| Hydrogen, liquid | I | kg | 3.60E-6 | market for hydrogen, liquid – RER |
| Municipal solid waste | I | kg | -0.0011 | market for municipal solid waste – CH |
| Natural gas, high pressure | I | $m^3$ | 0.00096 | market to natural gas, high pressure – Europe without Switzerland |
| Natural gas, high pressure | I | $m^3$ | 0.11597 | market group for natural gas, high pressure – Europe without Switzerland |
| Wastewater, from residence | I | $m^3$ | -0.00035 | market for wastewater, from residence – RoW |
| **OUTPUT FLOWS** | | | | |
| **Name** | **Type** | **Unit** | **Value** | **Destination process** |
| Carbon dioxide, fossil | E | kg | 0.693 | Emission to air/unspecified |
| Carbon monoxide, fossil | E | kg | 5.00E-5 | Emission to air/unspecified |
| Hydrogen chloride | E | kg | 9.25E-5 | Emission to air/unspecified |
| Hydrogen fluoride | E | kg | 2.10E-5 | Emission to air/unspecified |
| Nitrogen oxides | E | kg | 0.00327 | Emission to air/unspecified |
| NMVOC, non-methane volatile organic compounds, unspecified origin | E | kg | 5.00E-5 | Emission to air/unspecified |
| Particulates, < 2.5 um | E | kg | 0.00018 | Emission to air/unspecified |
| Particulates, > 10 um | E | kg | 2.30E-5 | Emission to air/unspecified |
| Particulates, > 2.5 um, and < 10 um | E | kg | 2.30E-5 | Emission to air/unspecified |
| Sulfur dioxide | E | kg | 0.00404 | Emission to air/unspecified |
| Tin | E | kg | 9.13E-6 | Emission to air/unspecified |
| Water | E | kg | 0.27125 | Emission to air/unspecified |
| Water | E | $m^3$ | 7.875E-5 | Emission to water/unspecified |

*Table C.7 : Model of the process for recycling of 1 kg steel waste, based on the process "Steel production, electriciy, low-alloyed – RER" – E: elementary flow, I: Intermediate flow*

| **INPUT FLOWS** | | | | |
|---|---|---|---|---|
| **Name** | **Type** | **Unit** | **Value** | **Provenance process** |
| Anode, for metal electrolysis | I | kg | 0.003 | market for anode, for metal electrolysis – GLO |
| Dust, unalloyed electric arc furnace steel | I | kg | -0.0096 | market for dust, unalloyed electric arc furnace steel – GLO |
| Electric arc furnace converter | I | Item | 4.00E-11 | market for electric arc furnace converter – GLO |
| Electricity, medium voltage | I | kWh | 0.42361 | market group for electricity, medium voltage – RER |
| Hard coal | I | kg | 0.0022 | market for hard coal – WEU |

| | | | | |
|---|---|---|---|---|
| Hard coal | I | kg | 0.0118 | market for hard coal – PL |
| Inert waste, for final disposal | I | kg | -0.005 | market for inert waste, for final disposal – CH |
| Natural gas, high pressure | I | m$^3$ | 0.0248 | market group for natural gas, high pressure – Europe without Switzerland |
| Natural gas, high pressure | I | m$^3$ | 0.0002 | market fort natural gas, high pressure – CH |
| Oxygen, liquid | I | kg | 0.05073 | market for oxygen, liquid – RER |
| Refractory, basic, packed | I | kg | 0.0135 | market for refractory, basic, packed – GLO |
| Slag, unalloyed electric arc furnace steel | I | kg | -0.0928 | market for slag, unalloyed electric arc furnace steel – GLO |
| Water, cooling, unspecified natural origin | E | m$^3$ | 0.00522 | Resource/in water |
| **OUTPUT FLOWS** | | | | |
| **Name** | **Type** | **Unit** | **Value** | **Destination process** |
| Benzene | E | kg | 2.285E-6 | Emission to air/unspecified |
| Benzene, hexachloro- | E | kg | 2.00E-8 | Emission to air/unspecified |
| Cadium | E | kg | 3.65E-8 | Emission to air/unspecified |
| Carbon monoxide, fossil | E | kg | 0.00232 | Emission to air/unspecified |
| Chromium | E | kg | 1.254E-6 | Emission to air/unspecified |
| Copper | E | kg | 2.305E-7 | Emission to air/unspecified |
| Dioxins, measured as 2,3,7,8-tetrachlorodibenzo-p-dioxin | E | kg | 4.535E-12 | Emission to air/unspecified |
| Hydrocarbons, aromatic | E | kg | 7.7008E-5 | Emission to air/unspecified |
| Hydrogen chloride | E | kg | 5.2E-6 | Emission to air/unspecified |
| Hydrogen fluoride | E | kg | 2.35E-6 | Emission to air/unspecified |
| Lead | E | kg | 1.808E-6 | Emission to air/unspecified |
| Mercury | E | kg | 2.238E-6 | Emission to air/unspecified |
| Nickel | E | kg | 7.005E-7 | Emission to air/unspecified |
| Nitrogen oxides | E | kg | 0.00018 | Emission to air/unspecified |
| PAH, polycyclic aromatic hydrocarbons | E | kg | 3.725E-8 | Emission to air/unspecified |
| Particulates, < 2.5 um | E | kg | 0.00017 | Emission to air/unspecified |
| Particulates, > 10 um | E | kg | 5.875E-5 | Emission to air/unspecified |
| Particulates, > 2.5 um, and < 10 um | E | kg | 0.00017 | Emission to air/unspecified |
| Polychlorinated biphelys | E | kg | 2.325E-8 | Emission to air/unspecified |
| Sulfur dioxide | E | kg | 7.7E-5 | Emission to air/unspecified |
| Water | E | kg | 2.92117 | Emission to air/unspecified |
| Water | E | m$^3$ | 0.00230 | Emission to water/unspecified |
| Zinc | E | kg | 2.294E-5 | Emission to air/unspecified |