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Combining Building Information Model and Life Cycle Assessment for Defining Circular Economy Strategies

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Abstract: Although the construction industry has the potential to implement circular economy (CE) principles, the sector suffers from a veritable lack of initiatives to develop circular and regenerative design principles. However, existing buildings intended to be demolished could be considered as material banks for future constructions, with the aim to exploit anthropogenic resources, extend material/product efficiency, and reduce the extraction of natural resources. This concept of buildings as material banks is being studied more and more in the scientific literature, but it still requires the existing building stock to be fully digitalized, thus making materials reusable in new buildings starting from the architectural design stage. Moreover, the decision process regarding CE strategies requires the consideration of the environmental impacts of the deconstruction and end-of-life processes, which is essential in CE implementation. This paper introduces a digital platform for generating materials inventory and supporting the definition of reuse strategies. Then, by using digital tools in combination with life cycle assessment (LCA) studies of the deconstruction process and output of materials and components inventories, a method is defined and tested on a pilot building in Luxembourg.

Keywords: circular economy; life cycle assessment; building information modeling; material reuse; construction industry

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1. Introduction

In their study, Hickel et al. [1] demonstrated that high-income countries, which represent 16% of the world population, are responsible for 74 percent of the global excess material use (i.e., 27% for the USA and 25% for the EU high-income countries and the UK, respectively). Of course, resource depletion and pollution generated by resource extraction and transformation make our economic model unviable as the planet Earth is physically limited [2]. In recent years, governments realized that the linear take–make–waste economy must be replaced as it exposes societies and businesses to multiple risks [3] and that we urgently need a transition to a circular economy (CE) that promotes "*an economic and industrial model that is restorative and regenerative by design*" [4]. A CE relies on the idea of extension of products, materials, and resources life spans ([5,6]). It contributes to building an economic, natural, and social capital based on the following three principles: *design out waste and pollution*, *keep products and materials in use*, and *regenerate natural systems* [4]. In his "*plea for a circular economy that grows*" [7], Kirchherr argues that "*an economy that increases its GDP, circularity, and sustainability at the same time is both desirable and conceivable*". The benefits of an economy based on resource efficiency have been recognized. Wijkman et al. [3] demonstrated in their work that for five European countries (i.e., Sweden, Finland, The Netherlands, France, and Spain), a shift towards a CE will contribute to reducing emissions by 66 to 69% and also to significantly boost job creation. CE will require changes at the macro and micro levels, respectively, aiming at creating opportunities to reach net negative CO_2 emissions and re-programming governance to re-balance the profit and improve sustainable performance [8]. Even if CE is subject to multiple interpretations and implementations in the literature, it appears more and more clearly that alliance between consumers, producers, policymakers, and scholars is a key component for enabling CE and that technological innovations will play a major role as drivers of CE [9]. CE will contribute to more sustainable sociotechnical systems [10] and will be at the origin of new sustainable business models.

Although the construction industry has a real potential to implement CE principles, the sector suffers from a veritable lack of initiatives to develop CE and regenerative design principles. Yet the industry is responsible for at least 37 percent of the global emissions [11]. Until now, most actions regarding the development of the sector have been concentrated on the "operational carbon" (i.e., the total carbon emissions produced during the stage of use of the building by occupants) but not on the reduction in the "embodied" carbon emissions from the design, production, and deployment of building materials [11]. The latter is expected to increase in proportional importance due to novel energy-saving technologies for the operation stages. In the EU, construction and demolition waste (CDW) constitutes 37.5% of the EU's total waste generation [12]. Since the EU Waste Framework Directive [13], the objective of 70% by weight target for the recovery of construction and demolition waste (CDW) has been reached in most of the EU countries [14]. Nevertheless, most of the CDW is still used for backfilling operations and not for reuse (i.e., with the fulfillment of the original function and not downcycling), which remains below 1% [15]. This indicates a clear gap, hindering actual CE implementation in practice.

We can observe that old buildings intended to be demolished have a high potential for CE, but the construction industry needs technological innovations to support the digitalization of these buildings and promote new CE practices that aim at increasing the reuse of materials and focus on sustainability performance. This will require the decision process regarding CE strategies to take into consideration the environmental impact of the deconstruction and end-of-life processes, which is essential in such implementation. This paper elaborates on a digital process in two steps dedicated to (1) the characterization of the composition of buildings in terms of materials and (2) the life cycle assessment (LCA) analysis for the environmental impact assessment of the deconstruction and reuse strategy. With regard to the paper structure, we first present the existing research works about the characterization of the existing building stock in terms of materials. Then, we introduce our methodology and formulate a proposition relying on a digital process and an integrated platform developed in the framework of the Interreg North-West Europe Digital Deconstruction (DDC) project. This application is intended to support the analysis of building material reuse strategies and is the result of a collaboration between AEC (Architecture, Engineering, and Construction) professionals, owners, and researchers. Then, by using this platform in combination with life cycle assessment (LCA) studies of the deconstruction process and output of materials and components inventories, we formulate the method that was tested on a pilot building in Luxembourg. The results are shown and discussed. Finally, the key outcomes, limitations, and lessons learned are summarized.

2. Characterizing the Existing Building Stock before Deconstruction

As mentioned earlier, the construction industry has a significant impact on resource depletion and global emissions. Linear economy is unsustainable, and the sector is entering a phase of transformation. The recently published European Green Deal, which promotes an "economic growth decoupled from resource use" [16], the CE has gained attention in multiple sectors, including AEC (Architecture, Engineering, and Construction). Nevertheless, the construction industry still lacks initiatives that rely on CE principles and (digital) tools and methods that would support CE actions.

Morseletto [17] presents the main targets of CE (see Figure 1), which are applied in the literature as well as in the economic systems. The targets are grouped into five principal areas: efficiency, recycling, recovery, reduction, and design. In the framework of this research work, we consider that the targets of "resource efficiency" and "waste reduction" are key issues for the AEC sector. This new focus will profoundly impact the design of buildings as well as the architectural, engineering and (de)construction practices.

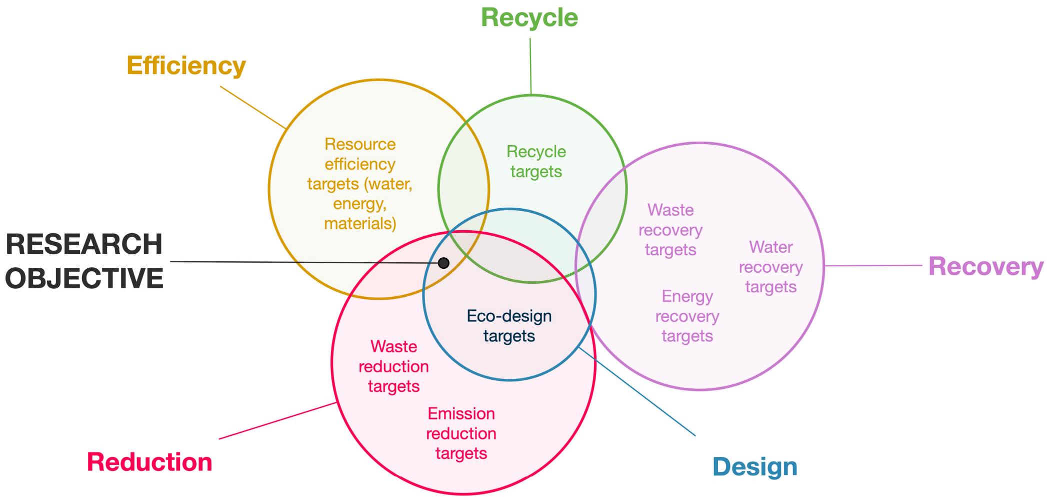

Figure 1. Main existing CE targets by areas of application (adapted from [17]).

2.1. Design for Disassembly and Urban Mining

Within the scientific literature dedicated to CE and construction, we can identify two major concepts that initiate the transformation of the sector towards circular construction with the aim to extend resource efficiency and reduce waste: (1) Design for Disassembly and (2) material banks and urban mining.

2.1.1. Design for Disassembly

Design for Disassembly (DfD) is an axis of research that focuses on new constructions and is based on diverse principles intended to make buildings easy to dismantle [18–21]. The buildings are, therefore, designed by taking into account the building's end-of-life and the deconstruction process at the early project phases. As defined in the norm ISO 20887:2020 [22], "*Design for disassembly devises explicit methods, prior to construction, for optimal recovery of specific products and materials without damaging either that which is being removed or surrounding components.*" These new principles of design transform the way architects and engineers design buildings. Making the building easy to disassemble implies integrating several concepts at the design and construction stages. In the literature, we can find several key requirements for DfD [21,23]: (1) collecting/creating documentation about materials and related deconstruction process; (2) choosing materials with consideration of the future impacts; (3) designing with easy-to-dismantle and accessible connections and joints; (4) separating non-recyclable, non-reusable and non-disposal components; (5) using of standardized components and dimensions; (6) designing for a safe deconstruction. These requirements would contribute significantly to preventing materials from being wasted when renovating or deconstructing the building and increase the reuse of materials. Of course, even if a norm has appeared, and certifications (e.g., LEED, BREEAM, DGNB) have encouraged such kind of practices in the last years, it is still challenging for professionals to implement these design principles as they do not control the schedule and cost, and they are facing a lack of materials that are designed aligned with these principles [21].

2.1.2. Existing Buildings as Material Banks and Urban Mining

The linear economy has contributed to the extraction of vast amounts of materials, which are mostly accumulated in urban areas [24]. This accumulation of materials is also known as anthropogenic resources, which have a huge potential for a circular economy and can replace the extraction of natural resources and become a source of raw materials. Urban mining can be defined as the "*integral management of the anthropogenic stock with the aim to recover raw materials from long-living products, buildings, infrastructure and tailings*" [25] cited in [26]. A large amount of the materials composing existing buildings might be valuable for reuse or recycling, but most of them lead to waste at the end of the life of the building. Urban mining is a CE strategy that suggests a systematic reuse of anthropogenic materials from the urban and built environment [27]. It differs from classic recycling as it requires the evaluation of the current and future availability of anthropogenic stocks, as well as a detailed characterization of the building stock, which is essential for future resource supply [28]. To support this need to characterize the building stock, the concepts of building as a material bank and material passport have emerged [29]. Material passports can be defined as "*(digital) sets of data describing defined characteristics of materials and components in products and systems that give them value for present use, recovery, and reuse*" [30]. Of course, due to the lack of information on existing (old) building stock, it is still challenging to define urban mining strategies [27]. Nevertheless, this new vision about the potential of CE of the building stock associated with new practices from demolition to careful deconstruction has already started to impact the architectural practice, and we can observe several initiatives of building designs composed of reclaimed materials (see [31]).

2.2. Digitalization for CE Practices in the Construction Industry

For multiple reasons, it is still difficult for AEC professionals to implement CE principles in their architectural projects, especially in designing new buildings based on reclaimed materials coming from deconstruction sites. The major reason is probably the difficulty in federating the multiplicity of actors that are involved in the decision process and keeping all the stakeholders (i.e., owners, architects and engineers, construction firms) involved and motivated by this change in practice because many barriers exist, which are elaborated in the literature [32–35]. For example, there is a lack of regulatory framework and dedicated insurance. Reusing materials from deconstruction in a new architectural design is often considered an additional risk for the architectural project (e.g., for the building stability or the security on-site, depending on the type of reclaimed product). The costs of dismantlement can be high, and the process can be long and have a high impact on the schedule and the total budget of the project. Moreover, the supply and demand are not well balanced, and there is a lack of market acceptance. Finally, there is a real need for methods and tools to characterize the composition of buildings in terms of materials.

It is on this last point that we decided to focus our research. Indeed, the idea that the existing building stock could be seen as a large material bank with a high potential to support new circular practices is increasingly shared amongst the scientific community. In the past few years, research works about digital technologies for CE practices in the construction industry have appeared [36–41]. Building information modeling (BIM), which is now key in architectural practice, has started to offer new opportunities for circular practices in construction [42,43]. Van den Berg et al. [44] explored the use of BIM to support the analysis of the existing conditions, the labeling of reusable elements, and the planning of deconstruction. Moreover, because of its capacity to centralize building data, BIM is expected to play a major role in urban mining [41]. In this paper, we consider that BIM-based processes and applications are essential to supporting the characterization of the composition of old buildings in terms of materials and the analysis of reuse scenarios at the end of the life of the building, including the assessment of the environmental impacts of the deconstruction. This should contribute to extending the life span of construction materials and products and their reuse in new architectural designs.

3. Methodology

The general methodology that has been deployed in the Interreg DDC project relied on several steps (see Figure 2), which describe the general process undertaken, from requirements analysis to platform development. This was described in previous scientific articles [45,46].

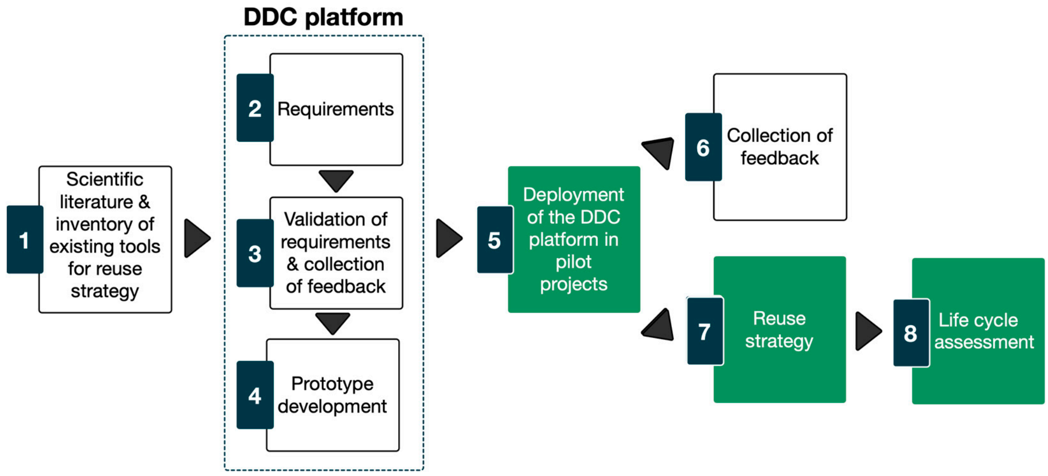

Figure 2. Methodology of creation of the DDC platform and validation in the Digital Deconstruction project.

In order to develop the DDC platform, which aims at supporting reuse strategy for deconstruction projects, a typical platform development methodology was employed from the state-of-the-art scientific literature on circular economy for the construction industry and existing digital applications (1), following the definition of functional and non-functional requirements (2), feedback workshops with experts (i.e., AEC professionals and researchers) (3), and prototyping (4). Testing on mock BIM models and, later, real pilot projects (5) was necessary to validate the DDC platform, which has been made available under an open-source license here (https://github.com/LIST-LUXEMBOURG/digital-deconstruction-platform-backend (accessed on 2 May 2024), https://github.com/LIST-LUXEMBOURG/digital-deconstruction-platform-frontend (accessed on 2 May 2024)). This entire process allowed us to digitalize the materials inventory (composite elements with materials, quantities, etc.) and support reuse strategy analyses (7). Throughout the deployment of the platform, feedback from professionals involved in the pilot projects was collected (6). To support step (8), we adopted an LCA methodology to assess the end-of-life (EoL) materials to deconstruct, thus calculating their impacts in 2 distinct scenarios: (a) business as usual and (b) deconstruction for reuse. While the ISO 14040/44 [47] suite of standards defines environmental LCA and a general framework for conducting it, these offer generic guidelines, and practical implementation is not specified in detail [48]. These, in turn, are complemented by EN 15978:2011 [49] for the buildings' use case and 15804:2012 [50] for products. In terms of calculation methodology, the case study investigated within this paper (Section 5) uses the Environmental Footprint 3.1 method [51] for the characterization of the environmental impacts of waste building materials management. In particular, it focuses on the evaluation of the end-of-life environmental impacts of four building materials calculated using the Circular Footprint Formula (CFF) [52] applied to simulate the aforementioned scenarios (a,b). A detailed description of the scopes, assumptions, and formulas is provided in Section 5.2, and they are then discussed together with the results in Section 6.

Within this paper, we focus on the three steps that are highlighted in Figure 2: (1) the deployment of the DDC platform and the related digital process of data collection in a pilot project for the generation of materials inventory (step 5); (2) the choices made in this pilot project regarding the reuse strategy (step 7); (3) the environmental impact of this reuse strategy based on LCA methodology (Step 8).

4. DDC Platform and BIM-Based Digital Process for Reuse Strategy

This section introduces the DDC platform, its scope and functionalities, the digital processes developed for the creation of the materials inventory, the scenario of reuse, and the LCA analysis.

4.1. General Concept of the DDC Platform

As mentioned earlier, the construction industry requires technological innovations to support the digitalization of old buildings that are planned to be demolished and promote new CE practices encouraging the reuse of materials. That is precisely the aim of the DDC platform. It was envisaged that data provided by several external technical modules would be combined to support reuse strategy analysis (see Figure 3 and [45] for more details). Throughout the duration of the project, several external modules were tested, and we used the DDC platform to centralize the outputs of these modules to display aggregated data in the dashboard and interact with BIM-based visualizations. In this pilot project, the following technical modules were used to digitalize the deconstruction process:

- *Three-dimensional scan* (TM1)—A combined point-cloud and photogrammetry technique [53,54] is used to collect data about the existing building to be deconstructed. It supports the first step of the digitalization process, which is identifying key components and materials and serving as a reference for BIM modeling.
- *Reversible BIM* (TM2)—An as-built BIM model was created. The modeled building and its major components were analyzed for their reuse potential using the methodology by [19]. This method considers the types of components, their connections, materials, quality, damage, and additional factors to make a reversibility assessment. An Industry Foundation Classes (IFC) model is exported based on this, which is then imported into the platform, and their reusability properties are calculated.
- *Materials inventory* (TM3)—The as-built reversibility BIM model in IFC is parsed, and a deconstruction inventory is created based on the DDC data model. Most notably, this allows a flexible view of the building as a bank of “elements” and/or “materials”, along with additional properties, indexes, and a BIM viewer as a reference to geometry and physical localization. The data model allows for the annotation of each element with classification code, reuse properties, and physical quantities, which can be used to calculate additional properties, such as the environmental impacts, as shown in the second part of this article.
- *Material passport and blockchain-based ownership tracking* (TM4)—The DDC platform was designed to attribute an identity to each building element in a BIM-based worldview. This identity, along with specific properties, was used to generate material passports by an external module and platform, which was then linked to the blockchain. This, however, is out of the scope of this paper.

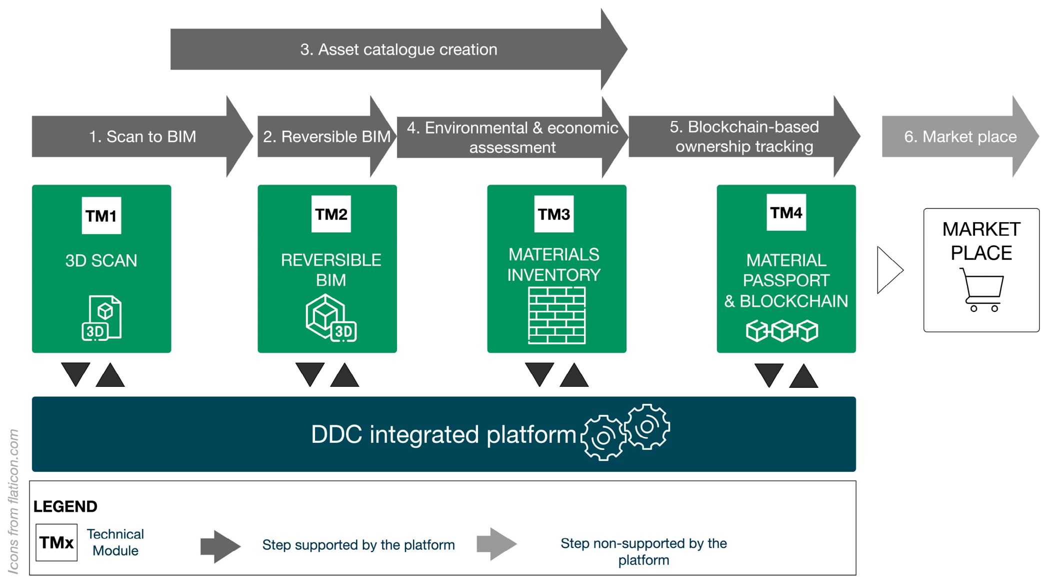

Figure 3. Concept of the Digital Deconstruction Platform.

4.2. Digital Process towards BIM-Based Materials Inventory and LCA Analysis

Throughout the process, several tools (described as modules M1–M4 above) were used to collect data about the pilot building and systematically digitalize information about it. During this pipeline, the collected information is transformed and interpreted several times based on the following steps (see Figure 4):

(1) Scan-to-BIM—Based on the point-cloud scan, an as-built BIM model is created (manually) with basic geometry in place (LOD250-300). The as-built BIM model is checked against existing plans to correct and/or adapt inaccuracies. The BIM model components are annotated with materials and their quantities (areas, volumes, masses, lengths, etc.). The BIM model was created by GTB-Lab (https://www.gtb-lab.com/ (accessed on 2 May 2024)) using Autodesk Revit, according to their modeling practices, to facilitate the reusability analysis [19,55], also mentioned above.

(2) BIM-to-IFC—The as-built BIM was exported to an IFC format, along with explicit properties and quantities for each component (volumes, areas, etc.).

(3) IFC extraction—The model is parsed and imported into the DDC platform, which creates inventories according to the DDC data schema and deals primarily with elements, element types, and material types that are interconnected.

(4) Scenario creation—The DDC data model provides additional properties to annotate the elements. Most notably, the property called "reuse decision" is of importance here for the creation of different reuse scenarios. Each element can be assigned a "reuse decision" based on the existing information but also based on what is possible in reality. The combinations of reuse decisions for the entire deconstruction project can thus vary greatly.

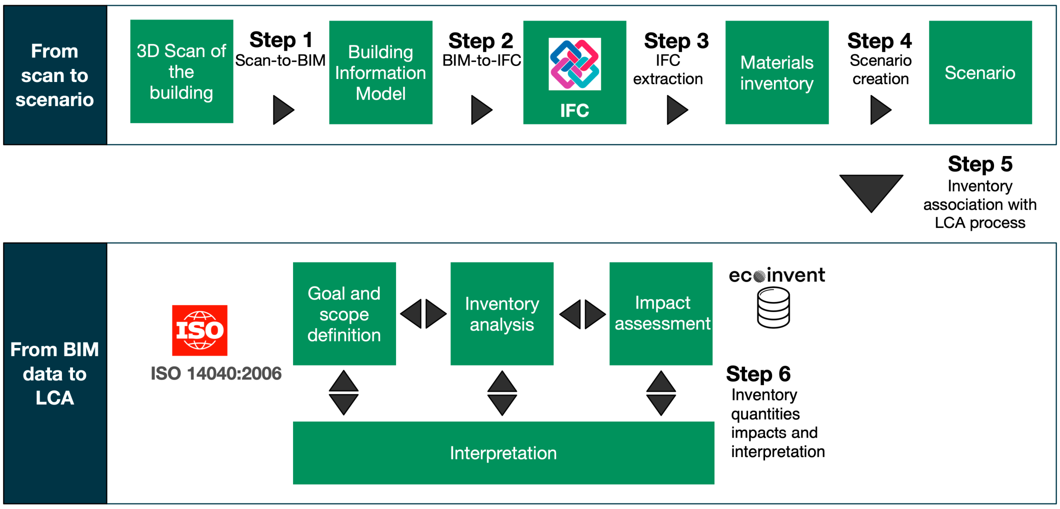

Figure 4. The digital process of data collection and LCA for the environmental impact assessment of the deconstruction.

The steps described above constitute the initial scope of the DDC platform, which would output basic statistics on the materials inventory as a whole. For the purposes of this study reported in this paper, we added two extra steps to incorporate LCA consideration:

(5) Inventory association with LCA processes—Depending on the type of element, its embedded materials, and the processes around it (deconstruction process, on-site tools used, transport, etc.), we define custom LCA processes. The reuse decision is also taken into account. A per unit factor is calculated (/m, /kg, etc.). These are detailed in Section 5.2, based on the types of components selected.

(6) Inventory quantities impact and interpretation—The scenarios are computed based on the reuse decision and the per unit factors of each component or material within the inventory, calculating the sum of impacts in several impact categories.

The outputs of the process allow for the dynamic re-calculation of impacts for the deconstruction inventories, which go beyond the typical product stage, as the processes at step 5 should include more accurate end-of-life estimates. This process involves desk work on the typical processes in the country of origin, which are detailed for Luxembourg below as part of the case study.

5. A Case Study in Luxembourg

The aim of the case study was first to deploy the DDC integrated platform and the associated BIM-based digital process on a real deconstruction project and then to analyze the environmental impact of the reuse strategy, which was implemented on the deconstruction site. This paper refers to a deconstruction project in Ettelbruck in Luxembourg. As in many EU countries, circular economy and CDW waste have been major concerns, especially for the last few years. The Law of 21 March 2012 [56] and its recent modification in 2022 [57] define the obligations for waste management in Luxembourg. The text notably mentions that a pre-demolition audit is required for deconstructing a building with a built volume higher than 1200 m^3 and generating at least 100 m^3 of waste. Also, hazardous materials must be treated separately in order to avoid the contamination of the non-contaminated waste. The law encourages measures for reuse and preparation for reuse. The building was an old building constructed in 1862, which was the property of Luxembourg National Railway Company (see Figure 5). This building was deconstructed in 2022 as the place is intended to support a strategy of a multimodal exchange hub. In this context, the decision was made to prevent some construction materials from waste.

Figure 5. View of the Ettelbruck train station.

5.1. BIM-Based Digital Process for Materials Inventory and Reuse Strategy

Supported by the DDC platform and related BIM-based digital processes regarding materials characterization and inventory, demolition waste was reclaimed. Following the digitalization process described in Section 4.2., a materials inventory (see Figure 6) was created based on quantities extraction from the BIM model, and a reuse strategy was defined based on the reuse potential of the building elements, dismantlement tests, and general opportunities of reuse in other buildings.

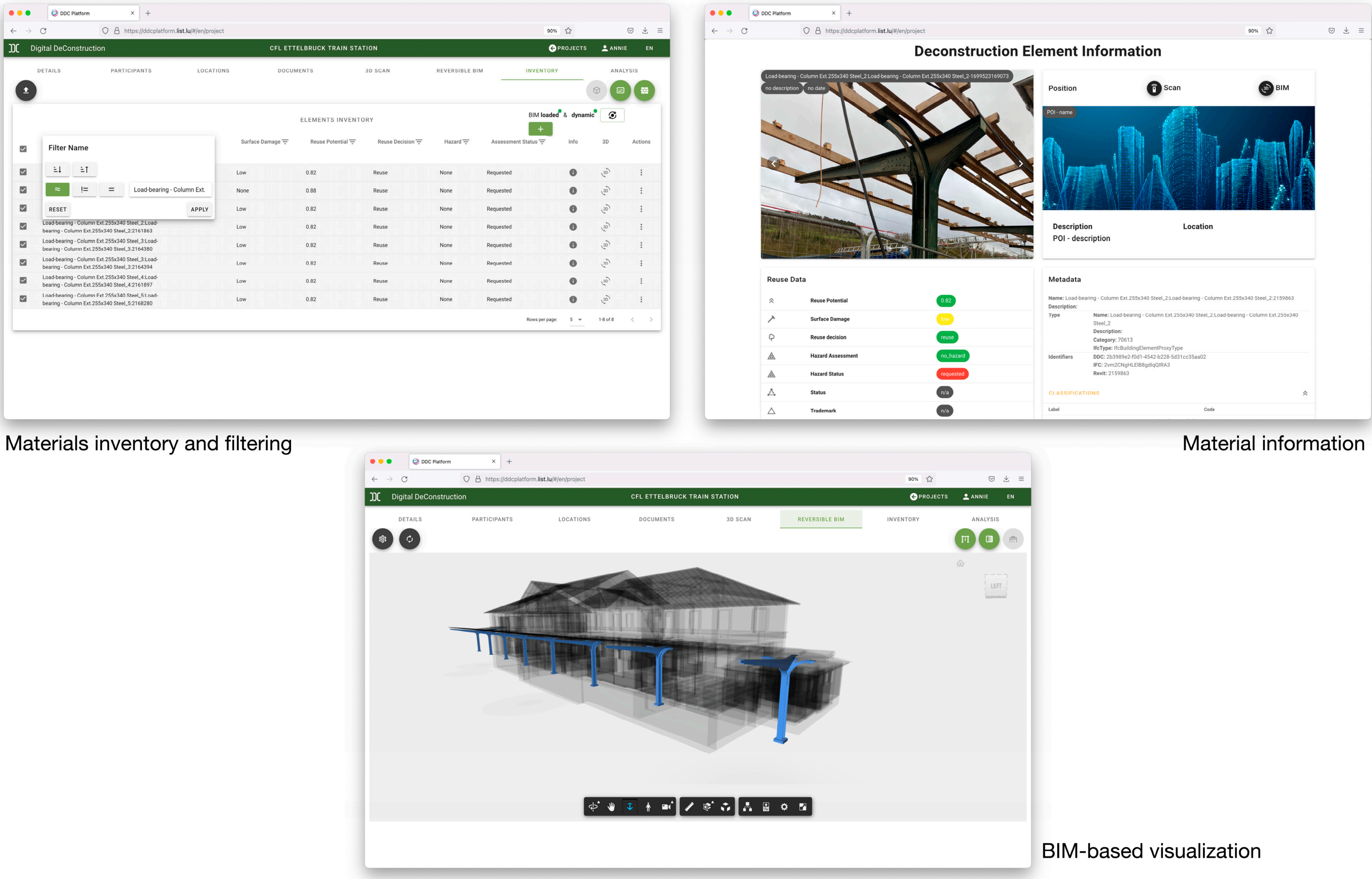

Figure 6. Interfaces of the DDC platform (inventory of materials and filtering, details of a building element, and BIM-based visualization).

It was decided to reclaim the following materials (see Table 1):

- The walls were constructed in stones, and the sandstone bricks that were used for the facade (i.e., decorative sandstone bricks) were reclaimed. The others (quarry stones) were crushed as in usual practice.
- Wood beams essentially from the framework were reclaimed as they had a high potential for reuse and were easy to dismantle.
- The steel beams from the canopy structure were reclaimed.
- The wood windows on the first floor of the building were also reclaimed.

Table 1. Reuse strategy implemented on the pilot case.

Building Element	Total (kg)	Reuse (kg)	BAU (kg)
Steel beams	23,031 kg	23,031 kg	0 kg
Wood beams	10,944 kg	10,944 kg	0 kg
Sandstone bricks (decorative) and carry stones	1,520,148 kg	382,725 kg	1,137,423 kg
Wood windows	119.58 m^2	60.19 m^2	59.39 m^2

Table 1 presents the quantities of materials that were reclaimed during the deconstruction stage. The estimations were performed based on quantities extracted from the BIM model. Of course, this implies that the consistency of the BIM model is crucial and that values may slightly differ from reality, as the BIM model was created at the deconstruction stage with a lower level of detail than in a classical as-built BIM model. The two scenarios, reuse and BAU, represent the different end-of-life choices for the total quantity of deconstructed materials. In the case of BAU, this indicates an end of life according to the conventional disposal techniques for each type of material, as defined in Appendix A.

Wooden frameworks, as well as stones, had a high potential for the renovation of historical buildings. After dismantlement, the components were stored, waiting to be reused in the renovations of a mill and a museum in Luxembourg.

5.2. LCA Methods for Assessing the Reuse Strategy

5.2.1. Assessment Methodology

The most consensual methodology for the evaluation of the environmental sustainability of products, processes, services, and even organizations is the life cycle assessment (LCA) methodology. The methodology is standardized by the ISO 14040/44 [47,58] and allows for a holistic evaluation of the potential environmental impacts occurring over the life cycle stages of the studied system, thus identifying potential environmental impacts shifting and guiding sustainable decision-making at different life cycle stages [59].

LCA methodology is divided into four main steps [47]. The first phase, goal and scope definition, establishes the objectives and settings of the study and defines the analysis scenarios, the system boundary, and the functional unit according to which the LCA results are quantified. The second phase is the life cycle inventory, during which all the required input and output data are quantified according to the defined scenario of analysis. Inventory data are differentiated between foreground data when directly linked to the processes under study and background data when reflecting all the upstream and downstream processes that support the foreground processes (e.g., supply chain processes for raw materials acquisition). All resources extracted and emissions generated by all the processes included during the inventory phase are quantified according to the defined functional unit. Those are translated into environmental impacts during the third stage, life cycle impact assessment. All the different environmental impacts from the system's flows are characterized according to the specific impact category characterization factor. In the last phase, results interpretation, all quantified environmental impacts are analyzed and evaluated in order to draw conclusions according to the goal(s) of the LCA.

While ISO 14044 provides the standardized framework on how to conduct the LCA, several life cycle impact assessment (LCIA) methodologies exist to evaluate the environmental impacts. In an effort to harmonize and uniform sustainability claims, the European Commission (EC) has developed the Environmental Footprint (EF) [51] methodology to be adopted at the European level.

The present study investigates the use of the EF 3.1 method for the characterization of the environmental impacts of waste and building materials end-of-use management. In particular, it focuses on the evaluation of the end-of-life environmental impacts of four building materials calculated using the Circular Footprint Formula (CFF) [52] (see Table 2) applied to simulate a business-as-usual end-of-life scenario and deconstruction for reuse scenario. The manufacturing stage, the end-of-life stage, the waste transport, the waste processing, and the potential circular benefits (through recycling and/or reuse) and/or the final disposal impacts are modeled using the CFF for each building materials, as described in Table 3.

Table 2. Detail and nomenclature of the CFF for each life cycle stage [52].

Stage	Formula
Manufacturing stage. Impacts from virgin and secondary material production	(1 − R1) × Ev + R1 (A Erecycled + (1 − A) Ev Qsin/Qp)
Waste processing for the recycling at the EoL of the building element	(1 − A) × R2 × (ErecyclingEoL − E × v (Qsout/Qp))
Waste disposal—incineration	(1 − B) × R3 × (Eer—LHV × Xer, heat − Ese, heat − LHV × Xer, elec × Ese, elec)
Waste disposal—landfilling	(1 − R2 − R3) × Ed
Transport impacts	Calculated separately and added

Table 2. *Cont.*

Where	
A: burdens and credits allocation factor between supplier and user of recycled material	Ev: impacts arising from the product manufacturing consuming virgin materials
R1: proportion of secondary material input that is recycled into a new product	Erecycled: impacts arising from the secondary material recycling process into the new product
R2: proportion of material that will be recycled/reused at the end of life	ErecycledEoL: impacts arising from the waste processing at EoL for the production of the secondary material (gate of the recycling process)
R3: proportion of material that is going to energy recovery	E × v: avoided impacts associated with the virgin material assumed to be substituted by the secondary material
Qsin: quality of the input secondary material	Eer: impacts of the energy recovery process
Qsout: quality of the output secondary material that arises from the recycling process	Xer, heat/elec: efficiency of the incineration process in producing heat and electricity from the combustion of waste
Qp: quality of the primary material that is substituted	Ese, heat/elec: avoided impacts associated with the energy source (heat and electricity) that is assumed substituted by the waste incineration
Ed: impacts associated with the disposal in landfill	LHV: lower heating value of the waste material that is incinerated

Table 3. Building life cycle stage from [50], data completeness and accuracy.

				Data Completeness/Accuracy
Building life cycle stage	Product	A1	Raw material supply	Representative data for the materials considered and modeled with materials available in the ecoinvent database
		A2	Transport	Not specified but included in the ecoinvent process, which refers to the A1 stage for a newly manufactured building element.
		A3	Manufacturing	Representative data for the processes considered and modeled with representative ecoinvent processes
	Construction process	A4–A5	/	Out of scope
	Use	B1–B7	/	Out of scope
	End of life	C1	Deconstruction/demolition	Calculated data partly based on assumptions and qualified estimates based on industrial experts.
		C2	Transport	Measured data for this specific case, from the deconstruction site to the recycling and reuse site, depending on the scenario.
		C3	Waste processing	Representative data provided by the operator for this specific case.
		C4	Disposal	Representative data provided by the operator for this specific case.
Supplementary information	Reuse Recovery Recycling	D	Benefit and loads beyond the system boundary (reuse, recovery, recycling)	Representative data provided by the operator for this specific case.

As the focus of this study is on the end-of-life waste management for each building element, to ensure comparability between the two scenarios, future material reincorporation cycles were not considered, and the manufacturing phase was therefore set equal for both scenarios (R1 = 0). Also, as it can be assumed that the quality of the recovered building element is considered equivalent to a new one, the value of Qsout/Qp = 1. This assumption is based on the fact that all deconstructed building elements were retrieved without damage and, therefore, considered to have the same quality as a new one. The share of a building element that was damaged during deconstruction was accounted for in the BAU scenario for the same building element.

The environmental impacts of the disposal of each building element were evaluated according to 6 impact categories out of the 16 impact categories included in the EF 3.1 (see Table 4).

Table 4. Impact categories from EF 3.1 [51] selected for the study.

Impact Category	Acronym	Unit	Description
Climate change	CC	kg CO_2-eq	Radiative forcing of GHGs over 100 years
Human toxicity, cancer	HTc	CTUh	Increased cancer diseases in the human population
Acidification	Ac	molc H+-eq	Critical load exceedance in terrestrial ecosystems due to acidifying substance deposition
Land use	LU	-	Index of soil quality
Water use	WU	m^3 depriv.	Deprivation-weighted water consumption
Resource use, fossils	FR	MJ	Fossil resources depletion based on lower heating values
Resource use, minerals and metals	MR	kg Sb-eq	Mineral and metals resource depletion based on use-to-availability ratio

5.2.2. Goal and Scope Definition

The goal of the study is to evaluate the environmental impacts of the deconstruction and recovery of four building elements through possible circular economy loops compared to a conventional demolition approach. Two scenarios are compared: (1) a conventional demolition and materials recovery scenario (business as usual (BAU)) and (2) a deconstruction and materials reuse alternative scenario (reuse).

Four types of building elements recovered from the Ettelbruck train station building renovation project are assessed: (1) wood beams; (2) steel beams; (3) natural stone bricks; (4) wooden windows.

The study focuses on the building end-of-life and waste disposal scenarios. The system boundaries include the passenger building deconstruction, transport, and end-of-life management of the four identified building elements. A comparative "gate to grave" analysis is performed for each of the recovered building components where in the first scenario, the grave is the conventional end of life of the building material, and in the comparable reuse scenario, it is the reutilization in a future building (see Figure 7). Since the aim of the study is the evaluation of the impacts associated with the sourcing of a building element or material from an existing deconstructed building compared to the sourcing of the same building element and material as a newly manufactured product (i.e., use of a second-hand product rather than brand new one), the construction and the use phases of the building are considered out of scope. The transport of raw materials (stage A2) is relevant only for the newly produced product, and it is considered in the ecoinvent process that supplies the raw materials to the gate of the manufacturing site (stage A3).

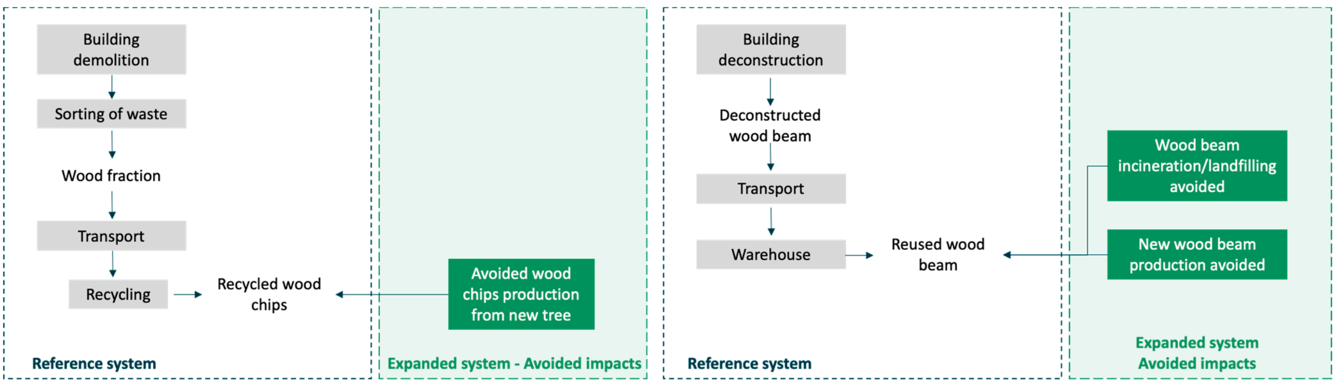

Figure 7. System boundary under study for the BAU and reuse scenario (e.g., wood beams).

The functional unit (FU) is defined as the end of life of 1 kg of the material of the building element demolished or deconstructed from the Ettelbruck train station passengers' building. For the wooden window, the FU is 1 m^2. To adjust all reference flows to 1 m^2, the average mass composition of 1 m^2 of a single glazed wooden window is extrapolated from public Environmental Public Declarations (EPDs) (see [60]), and all reference flows are adjusted accordingly.

5.2.3. Life Cycle Inventory

The life cycle inventory (LCI) lists all the processes used to evaluate the impacts of each building element disposal scenario according to the different stages of the CFF (Table A1 in Appendix A).

Conventional Demolition

The BAU demolition scenario is based on the typical waste management practice in Luxembourg or modeled according to the waste management practices reported by the engineering office in charge of the predemolition audit. Data collected in previous studies are used as a reference for disposal practices. Appendix A lists all the selected ecoinvent databases 3.9.1 for the conventional demolition EoL modeling.

Deconstruction Scenarios

The modeling of the deconstruction scenario is based on the procedure communicated by the engineering office in charge of the predemolition audit to deconstruct each type of building element. Specific primary data for the energy consumed during the deconstruction phase are not available; therefore, deconstruction impacts are estimated in terms of energy consumed per ton of material removed. Corresponding ecoinvent processes are listed in Table A2 in Appendix B.

Transport of the Reclaimed Products and Recycled Materials

For both scenarios, the ecoinvent process "market for transport, freight, lorry >32 metric ton, EURO5—RER—transport, freight, lorry >32 metric ton, EURO5" is selected as the most representative. For the demolition scenario, distances are calculated based on the distance for each material type to the corresponding recycler (68 km), while for the reuse scenario, these are calculated as the distance traveled to the temporary warehouse and the subsequent transport to the new reuse site (105 km). To test the relative impact and importance of transportation between the two scenarios, sensitivity analyses were conducted (e.g., multiplying by two the distance between the deconstruction site and the new reuse site). It was found that a modification of distance (within realistic range for such application in Luxembourg or Europe) would not significantly modify the results interpretation and impact benefits from reusing these materials compared to the business-as-usual scenario.

5.2.4. EoL Scenarios Assumptions

To be able to apply the CFF to each scenario, for each building element life cycle stage, a corresponding ecoinvent process is selected for the manufacturing stage, for the EoL stage, and for the disposal for both scenarios. According to the PEF guide, foreground processes should be modeled using specific primary data; however, due to a lack of primary data on the manufacturing of all the assessed building elements, a generic ecoinvent v3.10 allocation, cut-off by classification, was used to select the most representative manufacturing process. For the deconstruction phase, detailed processes are selected following discussions with the engineering office in charge of the predemolition audit. All reference flows are expressed according to the building element functional unit of 1 kg (except for the windows for which the functional unit of 1 m^2 was applied).

The CFF evaluates the burdens and the benefits of a product at the life cycle stage where they occur and is allocated both to the waste producer and to the user of the recycled material via an allocation coefficient. It applies a "Recyclability substitution approach" where the benefits from the material recovery via recycling at the end of life and the reutilization of recycled material at the manufacturing stage are calculated as the avoided primary materials production impacts allocated between the waste producer that recovers materials at the end of life and the manufacturer that reuses recycled material.

In a deconstruction scenario, the avoided impacts from the reutilization of a deconstructed building element are equivalent to the avoided production of a new building element, whereas, in a conventional demolition scenario, the avoided impacts correspond only to the production of the secondary material from the recycling of demolition waste (see Figure 7).

The CFF takes into consideration the reincorporation of recycled material into a new product at the manufacturing life cycle stage. It allocates the benefits of re-employing secondary material into a new product via an allocation coefficient A. However, in this study, the parametrization of the A factor is set to zero (A = 0) as the building elements are considered made only from primary material (R1 = 0), and therefore, no credit should be given to the recycled content when modeling the manufacturing stage of the building element. Therefore, we want to allocate the environmental credits to the different types of end-of-life decisions while keeping the impact from manufacturing equal between the two scenarios.

6. Results and Interpretation

The results of the impact assessment of the end-of-life scenarios at the unitary level for each building element are presented in Table 5. These are shown as absolute values of each impact category for the reference FU both in 100% BAU and 100% reuse scenario. The reduction in impacts compared to the BAU per each type of category is also shown.

Table 5. Absolute values of the selected impact categories for the end-of-life impact for both scenarios at the unitary level (FU).

Building Element	Impact Category	Unit	BAU	Reuse	Avoided	
Steel beams	Climate change	kg CO_2 eq	8.29×10^{-1}	1.21×10^{-1}	-7.08×10^{-1}	−85%
	Land use	-	3.05×10^{0}	7.04×10^{-1}	-2.34×10^{0}	−77%
	Water use	m^3 eq. deprived	3.30×10^{-1}	5.92×10^{-2}	-2.71×10^{-1}	−82%
	Resource use, fossils	MJ	1.06×10^{1}	1.76×10^{0}	-8.80×10^{0}	−83%
	Resource use, minerals, and metals	kg Sb eq	2.88×10^{-6}	6.60×10^{-7}	-2.22×10^{-6}	−77%
	Human toxicity: carcinogenic	CTUh	2.37×10^{-8}	5.40×10^{-9}	-1.83×10^{-8}	−77%
Wood beams	Climate change	kg CO_2 eq	1.60×10^{-1}	1.13×10^{-2}	-1.48×10^{-1}	−93%
	Land use	-	2.03×10^{2}	1.65×10^{-1}	-2.02×10^{2}	−100%
	Water use	m^3 eq. deprived	7.06×10^{-2}	1.03×10^{-3}	-6.96×10^{-2}	−99%
	Resource use, fossils	MJ	2.56×10^{0}	1.77×10^{-1}	-2.38×10^{0}	−93%
	Resource use, minerals, and metals	kg Sb eq	5.49×10^{-7}	3.85×10^{-8}	-5.10×10^{-7}	−93%
	Human toxicity: carcinogenic	CTUh	2.01×10^{-10}	5.02×10^{-12}	-1.96×10^{-10}	−98%
Sandstone bricks and quarry stones	Climate change	kg CO_2 eq	1.33×10^{-1}	1.39×10^{-2}	-1.19×10^{-1}	−90%
	Land use	-	3.70×10^{-1}	1.66×10^{-1}	-2.03×10^{-1}	−55%
	Water use	m^3 eq. deprived	2.75×10^{-1}	1.02×10^{-3}	-2.74×10^{-1}	−100%
	Resource use, fossils	MJ	3.38×10^{0}	2.08×10^{-1}	-3.17×10^{0}	−94%
	Resource use, minerals, and metals	kg Sb eq	3.80×10^{-7}	3.54×10^{-8}	-3.44×10^{-7}	−91%
	Human toxicity: carcinogenic	CTUh	5.61×10^{-11}	5.77×10^{-12}	-5.03×10^{-11}	−90%

Table 5. *Cont.*

Building Element	Impact Category	Unit	BAU	Reuse	Avoided	
Wood windows	Climate change	kg CO_2 eq	6.18×10^1	3.30×10^{-1}	-6.15×10^1	−99%
	Land use	-	6.54×10^3	4.82×10^0	-6.53×10^3	−100%
	Water use	m^3 eq. deprived	3.44×10^1	3.00×10^{-2}	-3.43×10^1	−100%
	Resource use, fossils	MJ	7.27×10^2	5.17×10^0	-7.22×10^2	−99%
	Resource use, minerals, and metals	kg Sb eq	7.44×10^{-4}	1.12×10^{-6}	-7.43×10^{-4}	−100%
	Human toxicity: carcinogenic	CTUh	8.82×10^{-8}	1.46×10^{-10}	-8.81×10^{-8}	−100%

Deconstruction for reuse is always the least impactful option, with environmental impacts over 80% lower for almost all impact categories. The waste processing at the EoL in the CFF for the reuse scenario generates higher environmental credits as the avoided process is the manufacturing of a new building element, whereas, in the BAU scenario, the environmental credits are associated only with the avoided impacts from the extraction of primary virgin material equivalent to the secondary material recovered.

Figure 8 shows the climate change impacts (i.e., $kgCO_2eq$) for the selected building elements at the scale of the whole project. For each element, the GHG emissions are calculated for a baseline scenario in which 100% of the total quantity is disposed of according to conventional practices (BAU). Then, based on the actual quantities of each building element recovered, the impacts generated from the deconstruction and subsequent valorization (circular or reuse) are calculated. Finally, the emissions avoided thanks to the deconstruction approach are obtained as the difference between the impacts of the circular/reuse scenario and the conventional approach. The conventional BAU scenario considers that the waste is processed via what is considered the conventional recycling process and, therefore, assumes a certain amount of material recovery.

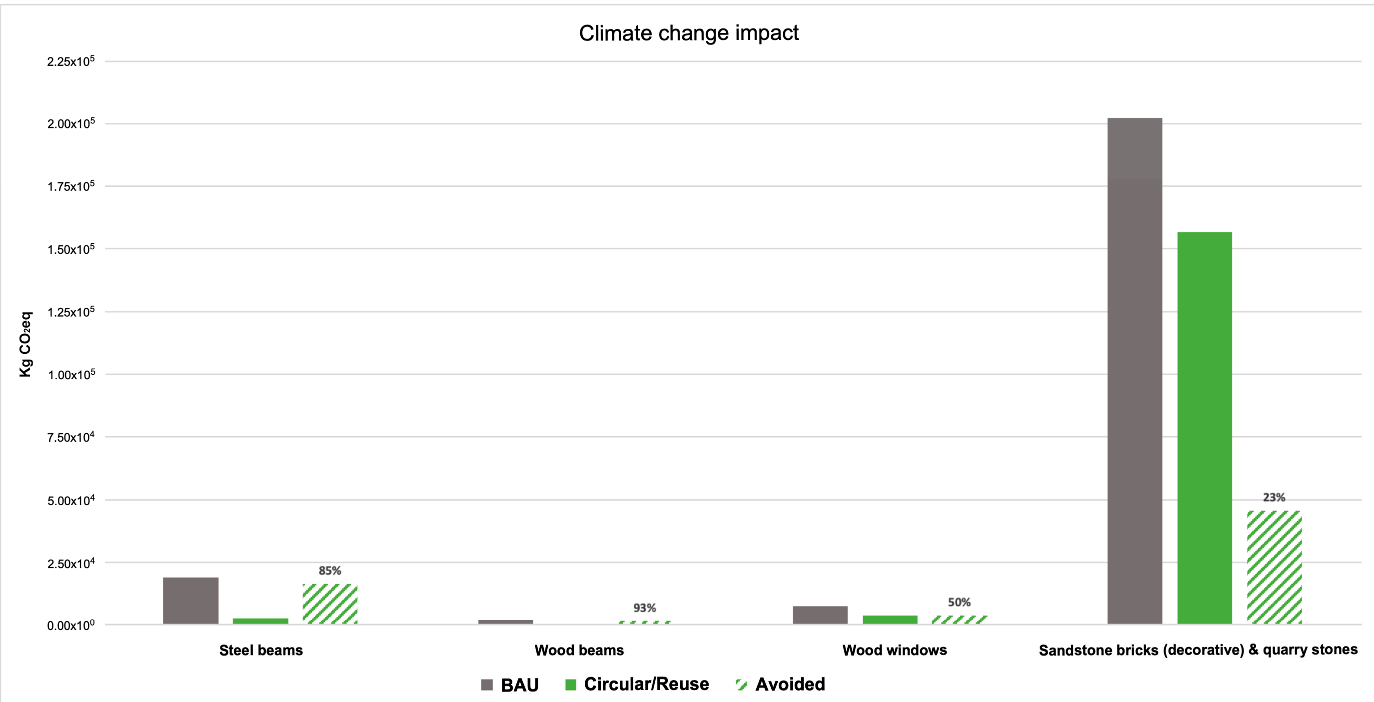

Figure 8. GHG emissions ($kgCO_2eq$) per each building element recovered in the project according to the conventional and deconstruction strategy. The % values refer to the amount of GHG emissions that have been avoided thanks to deconstruction and reuse.

From Figure 8, the biggest emissions are associated with the conventional disposal of the stone bricks and the quarry stones, which is influenced by the large quantity of available material compared to the others. Even though only a limited portion of the available material has been re-employed in a circular/reuse strategy, this results in the highest quantity of GHGe avoided in absolute terms (i.e., $4.56 \times 10^{+4}$). In terms of the share of avoided emissions, the wood beams (93%) and the steel beams (85%) are the most important as those building elements are almost entirely reused.

Figure 9, however, shows that in terms of intensity of emissions per unitary value of building element (i.e., 1 kg or 1 m^2), the window and the steel beam are the most emitting when disposed according to a conventional demolition scenario. For this reason, although at the project level, the wood windows were re-employed in a circular/reuse approach only for half of the recovered amount, a saving of $3.70 \times 10^{+3}$ $kgCO_2eq$ is nonetheless obtained (Table 6).

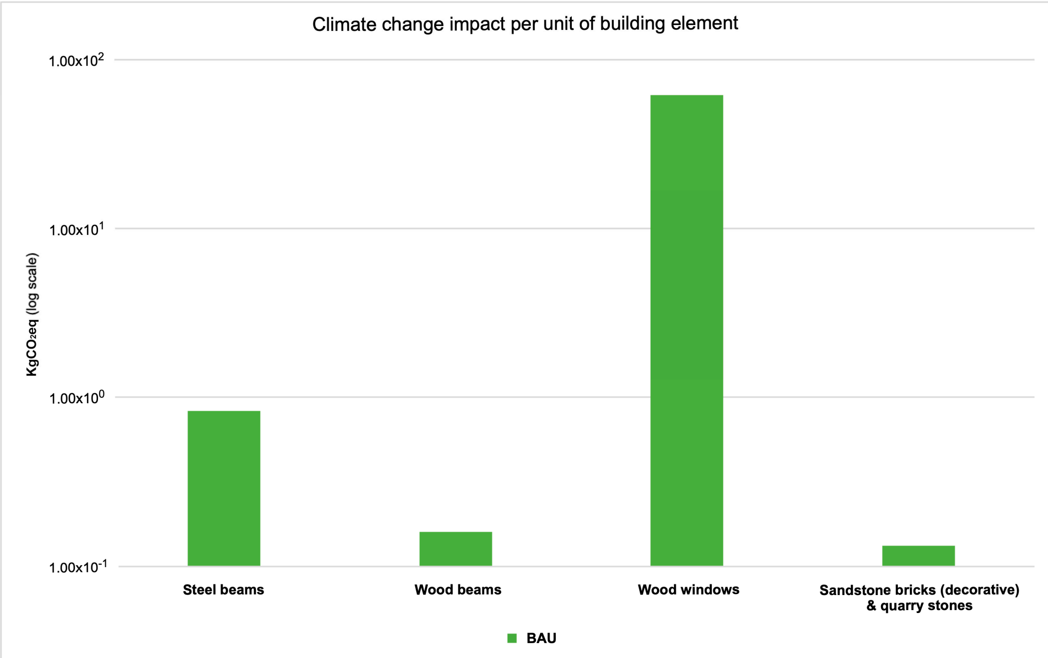

Figure 9. GHG emissions ($kgCO_2eq$) per each building element recovered per unitary values according to the BAU end-of-life scenario. Values are expressed in a logarithmic scale.

Table 6. Absolute values of the selected impact categories for the end-of-life impact for both scenarios at the scale of the project.

Building Element	Impact Category	Unit	BAU	Reuse	Avoided	
Steel beams	Climate change	kg CO_2 eq	0	2.79×10^3	1.63×10^4	85%
	Land use	-	0	1.62×10^4	5.40×10^4	77%
	Water use	m^3 eq. deprived	0	1.36×10^3	6.24×10^3	82%
	Resource use, fossils	MJ	0	4.05×10^4	2.04×10^5	83%
	Resource use, minerals, and metals	kg Sb eq	0	1.52×10^{-2}	5.11×10^{-2}	77%
	Human toxicity: carcinogenic	CTUh	0	1.24×10^{-4}	4.21×10^{-4}	77%

Table 6. *Cont.*

Building Element	Impact Category	Unit	BAU	Reuse	Avoided	
Wood beams	Climate change	kg CO_2 eq	0	1.24×10^2	1.63×10^3	93%
	Land use	-	0	1.81×10^3	2.22×10^6	100%
	Water use	m^3 eq. deprived	0	1.13×10^1	7.61×10^2	99%
	Resource use, fossils	MJ	0	1.94×10^3	2.61×10^4	93%
	Resource use, minerals, and metals	kg Sb eq	0	4.21×10^{-4}	5.59×10^{-3}	93%
	Human toxicity: carcinogenic	CTUh	0	5.49×10^{-8}	2.14×10^{-6}	98%
Wood windows	Climate change	kg CO_2 eq	3.67×10^3	3.69×10^3	3.70×10^3	50%
	Land use	-	3.88×10^5	3.89×10^5	3.93×10^5	50%
	Water use	m^3 eq. deprived	2.04×10^3	2.04×10^3	2.07×10^3	50%
	Resource use, fossils	MJ	4.32×10^4	4.35×10^4	4.34×10^4	50%
	Resource use, minerals, and metals	kg Sb eq	4.42×10^{-2}	4.43×10^{-2}	4.47×10^{-2}	50%
	Human toxicity: carcinogenic	CTUh	5.24×10^{-6}	5.25×10^{-6}	5.30×10^{-6}	50%
Sandstone bricks and quarry stones	Climate change	kg CO_2 eq	1.51×10^5	1.57×10^5	4.56×10^4	23%
	Land use	-	4.21×10^5	4.84×10^5	7.81×10^4	14%
	Water use	m^3 eq. deprived	3.13×10^5	3.13×10^5	1.05×10^5	25%
	Resource use, fossils	MJ	3.84×10^6	3.92×10^6	1.21×10^6	24%
	Resource use, minerals, and metals	kg Sb eq	4.32×10^{-1}	4.46×10^{-1}	1.32×10^{-1}	23%
	Human toxicity: carcinogenic	CTUh	6.38×10^{-5}	6.60×10^{-5}	1.93×10^{-5}	23%

All impact categories results at the scale of the project are shown in Table 6.

7. Limitations

In terms of the digitalized process described in Section 4.2, the DDC platform was envisaged to help streamline the entire process, which, from its initial scope, was expanded here to include LCA studies with a focus on the EoL stage. However, the process is highly fragmented, and the data are transformed across several stages, even more so for the inclusion of LCA methodologies, which require a lot of desk work effort. The assumptions have not been fully incorporated into the platform, but we consider the LCA to be an additional module external to the platform. The platform is limited to aggregating key information and provides quantities for the LCA study instead. The convenience lies in its link to the BIM model and the generation of deconstruction scenarios, which can be conveyed more easily to decision-makers thanks to visual/3D representations. The conversion and transformation of data provide an additional risk when it comes to quantity take-off as a result of an as-built BIM. For example, the representation of geometry and the internal structure of the building components might differ in reality, resulting in different volumes or masses of certain embedded materials. Thus, we encourage the keeping of the BIM model from design to deconstruction for more accuracy. This risk is mitigated here due to restricting the scope to key (generally bulky) elements, which were tracked on-site by the deconstruction company.

When evaluating a circular construction practice, it is important to be able to consider in a precise and transparent manner all the different circular loops that any material may have had before being incorporated into a building element. That is, a fair evaluation would require a specific list of all materials, their quality, and their origin to inform whether these have already been included in previous circular loops. This is fundamental to correctly allocate the different impacts generated or avoided during the different cascading loops resulting from the multiple choices of recovery, refurbishing, recycling, or reuse that can be made during the life cycle. This limitation is further increased when assessing or decommissioning a whole building element made of several materials.

This lack of complete documentation for the materials composition of the building element has forced this study to approximate the manufacturing impacts to the most representative ecoinvent process without being able to identify what represents a secondary material input from a primary one. This limitation would be even more important should the study involve multiple loops of remanufacturing stages.

This rigidity is also evident when modeling the waste processing at EoL. ErecyclingEoL should express the impacts deriving from the demolition/deconstruction operations at the building level and waste recycling processes on the production of secondary material, including transport to the recycling site. For the waste recycling process, we adapt processes that would refer to the recycling of the whole building element rather than the constituent materials when available. The avoided impacts would then be calculated on the main reference flow of the recycling process. For example, in the case of a wooden window, the main reference flow is considered wood, while the other materials are disposed of. However, this interpretation limits the representation of the true material recovery supply chain that, in reality, could be different from what is modeled by the ecoinvent process and, thus, the true evaluation of the potential benefits arising from a more efficient recycling process.

Finally, given the absence of specific primary data on both the demolition and the deconstruction energy consumption, assumptions are made using either generic literature values for energy consumption or adapting existing ecoinvent processes to the effective deconstruction operations.

8. Conclusions

In this paper, we highlighted the potential of digitalization for supporting reuse strategy when deconstructing a building, and we introduced a digital platform called Digital Deconstruction for generating a BIM-based materials inventory and supporting the definition of reuse strategies. Then, by using digital information flows in combination with life cycle assessment (LCA) studies of the deconstruction process and output of materials and components inventories, a method was defined and tested on a pilot building in Luxembourg. This study focused on four materials/components: steel beams, wooden beams, wooden windows, and stones (decorative and quarry stones). This has allowed for demonstrating that for these materials/components, deconstruction for reuse is always the least impactful option, with environmental impacts over 80% lower for almost all impact categories. Moreover, it has been found that a modification of distance (within a realistic range for such application in Luxembourg or Europe) does not significantly modify the results interpretation and impact benefits from reusing these materials compared to the business-as-usual scenario.

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Conflicts of Interest: The authors declare no conflicts of interest.

Appendix A

Table A1. Conventional demolition representatives ecoinvent processes.

Building Element	Conventional Disposal	Representative Ecoinvent Process
Stone bricks	Considering conventional practices, it was assumed that following demolition and sorting, stone bricks are sent to recycling facilities where they are crushed in smaller aggregates	"treatment of waste brick, sorting plant—Europe without Switzerland—waste brick"
Steel beams	As per Dolci et al. (2020) [61]	"steel production, electric, low-alloyed—Europe without Switzerland and Austria—steel, low-alloyed"
	This process considers only the energy consumed by the mechanical demolition machine	"treatment of waste reinforcement steel, recycling—CH—waste reinforcement steel"
Wood beams	Energy consumption of a conventional mechanical demolition machine is 60 MJ/ton, as per Di Maria (2018) [62]	"diesel, burned in building machine—GLO—diesel, burned in building machine"
	Recycling process	"treatment of waste wood, post-consumer, sorting and shredding—CH—wood chips, from post-consumer wood, measured as dry mass"
Windows wood	Energy consumption of a conventional mechanical demolition machine is 60 MJ/ton, as per Di Maria (2018) [62]	"diesel, burned in building machine—GLO—diesel, burned in building machine"
	Recycling process	"treatment of used window frame, wood, collection for final disposal—CH—used window frame, wood"

Appendix B

Table A2. Ecoinvent processes for the deconstruction scenario.

Building Element		Ecoinvent Process
Steel beams	Hydraulic digger to individually excavate to a depth of 50 cm from the base. It was, therefore, assumed that a volume of 0.5 m^3 was dug up to deconstruct each beam. The impacts from the digging were then referenced to 1 kg of steel by dividing the reference flow by the average weight of one beam (2300 kg).	"excavation, hydraulic digger—RER—excavation, hydraulic digger"
Wood beams	Individually dismantled with crowbar or/and saw. Reference energy consumption 2.04 kWh/ton	"Electricity, low voltage {LU} | market for | Cut-off, U"
Stone bricks	Dismantling via electrical chipping hammer. Reference energy consumption 2.04 kWh/ton	"Electricity, low voltage {LU} | market for | Cut-off, U"
Windows wood	Dismantling via electrical chipping hammer. Reference energy consumption 2.04 kWh/ton	"Electricity, low voltage {LU} | market for | Cut-off, U"

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