WPT1 System development

Deliverable 4.5

Overall economic and financial feasibility assessment

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1. Agreement form expectations

"The results of the analyses at pilot level (D.T1.4.4) will be synthesised to assess the overall economic and financial feasibility of the application of the DDC system. This assessment will allow the final calibration of the system under D.T1.3.4."

2. Objectives of the overall economic and financial assessment

One of the objectives of the Digital Deconstruction programme is to test and verify the relevance of the tools developed. To this end, a cost-benefit analysis will be carried out during the deployment of the tools on each pilot project.

Although the first request was a purely financial analysis, it was decided to add an environmental part to the study. This analysis is then made not only to identify the financial savings or additional costs linked to the Digital Deconstruction approach but also to highlight the environmental benefits it brings.

The goal is then to analyze and take a step back from the results of DLT.1.4.4: what are the costliest steps? What are the main environmental benefits? What are the best practices to retain? What factors play the most important role in achieving economic balance while improving environmental impacts?

As a reminder, the analysis is based on the following deliverables:

- **DT1.4.3 – CBA methodology: data collection tool**

The objective of this preliminary work was to provide a tool that will help evaluate the financial and environmental impacts of the Digital Deconstruction approach during the deployment of pilot projects to highlight the main benefits that can be achieved thanks to the approach and to enable the owners of technological bricks to improve the functionalities of their tools as the project progresses. This analysis tool was accompanied by a tool to facilitate the collection of the necessary data.

Three types of results were identified as expected from the cost-benefit analysis of the pilot projects and, more generally, from the Digital Deconstruction approach:

- Financial impact assessment
- Environmental impacts (carbon, material/waste, energy) assessment

- **DT1.4.4 – CBA at pilot level: results of the cost benefit analysis**

This deliverable lists all the costs and environmental impacts of three of the project's pilot projects: Gare du Nord (France), Ettelbruck station (Luxemburg) and Lomme (France).

Pilot	Business as usual	Selective deconstruction
Gare du Nord	810 960 € 0 tons reused	904 540 € 67 tons reused

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Ettelbruck station	578 500 € 0 tons reused	682 000 € 424 tons reused
Lomme	29 660 € 0 tons reused	36 920 € 5,4 tons reused

While this deliverable aimed to analyse each project individually, deliverable 4.5 will try to make a cross-analysis of theses project to highlight learning and good practice in achieving economic balance and maximising the environmental benefits of circular deconstruction projects.

3. Analysis of the financial impact of projects

First, as explained in the deliverable 4.4, there are not enough projects analysed to draw definitive conclusions on the cost differences of reuse. However, the results from the 3 analysed projects demonstrate that the cost increase associated with adopting circular practices, such as material reuse, is relatively modest and falls within the range of 10% to 25% when compared to conventional approaches.

In this analysis, it becomes evident that the initial costs of implementing a circular deconstruction strategy can be higher compared to a conventional approach. Indeed, the careful identification, removal, and processing of materials for reuse require additional labour and resources, leading to increased expenses during the deconstruction phase (that will be developed below).

While the resale and valorisation of materials generated from the deconstruction process generate revenue and contribute to reducing some of the supplementary costs, they may not be sufficient to achieve economic balance or direct financial gains for the project owners. The main financial benefits of adopting a circular deconstruction strategy are long-term and may manifest in reduced waste disposal costs, enhanced sustainability credentials, and potential indirect financial advantages.

Despite the financial challenges, it is essential to recognize that the circular deconstruction approach provides valuable environmental benefits, such as resource conservation, reduced carbon footprint, and enhanced circular economy principles.

3.1. Comparison of the financial impact of DDC pilot projects

Here's a comparison of the financial balances for each project, from the least to the most expensive. To enable a comparison between the projects, we have normalized the total deconstruction costs by calculating the cost per square meter (m^2) and the cost per total tonnage of materials. This normalization allows for a more equitable assessment, considering that projects vary significantly in terms of size, complexity, and material quantities.

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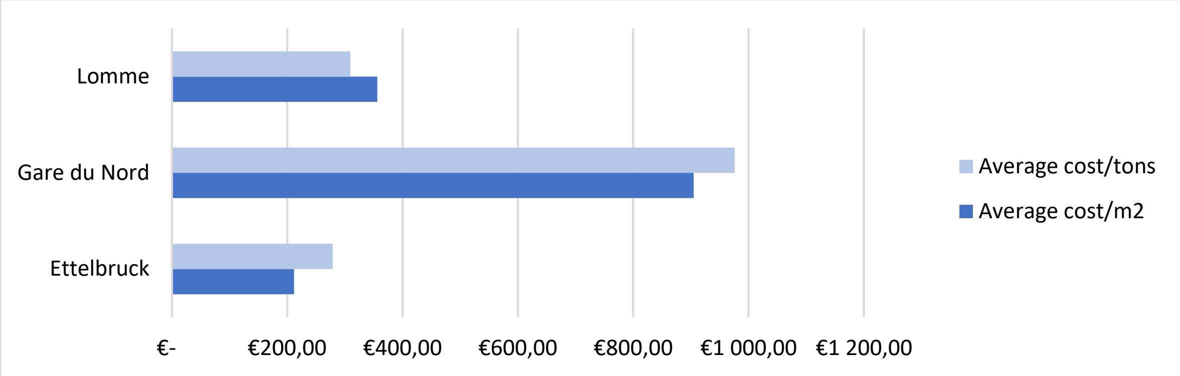


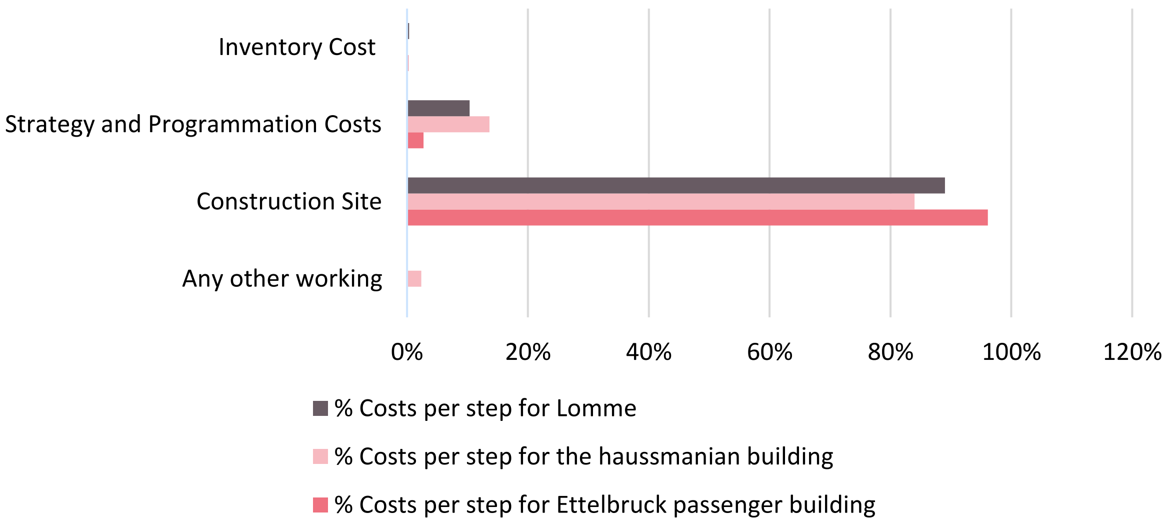
It is notable that the Gare du Nord project has the highest costs among the analysed projects. This could be attributed to its location in a dense urban area, where space for material storage is limited, and to the significant amount of time spent by the project team on strategy and programming, as they wanted to test new methodologies.

3.2. Identification of the costliest stages in a selective dismantling project

In general terms, in both traditional and selective deconstruction projects, the deconstruction phase tends to be the most resource-intensive and costly phase. During this phase, specialized labour, equipment, and resources are required to carefully dismantle and remove materials, ensuring their safe handling and transportation for further processing.

The costs associated with the deconstruction stage can include labour expenses, equipment rentals, waste removal, transportation, and any necessary safety measures. Additionally, the presence of hazardous materials, such as asbestos and lead, might incur extra costs for proper handling and disposal.

If we look at the pilot projects, here is the repartition of cost:



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We can draw several conclusions and from the analysis of costs of these three pilot projects:

- Digital Deconstruction Inventory: The costs associated with the inventory using digital tools are minimal for each pilot site, accounting for less than 1% of the total expenses. The implementation of digital tools does not significantly increase costs. However, it should be noted that this is R&D, so the pilot project owners do not have to pay for the development of the tools. Only their own time spent on the tools has been accounted for. If these practices were developed further, this cost could increase significantly.
- Strategy and programming: Achieving high-quality selective deconstruction necessitate the involvement of a specialized Reuse Assistance Mission (AMO). Currently, there might be little variation in AMO costs, as contracts are typically fixed. For instance, in the Lomme project, whether it involves selective deconstruction or demolition, the costs of NeoEco would remain the same since both scenarios require the mandatory PEMD diagnostic, resulting in similar fixed fees. Yet, engaging an AMO specialized in material reuse is crucial for successful and cost-effective projects. Investing in such expertise from the outset leads to better results and maximizes financial benefits.
- Valorisation: In certain cases, the resale of materials can offset treatment, storage, and transportation costs. For instance, the Lomme project exemplifies this, where the revenue generated from material resale (estimated at 19 619 €) helps balance out the expenses (estimated at 65 299 €).
- All steps: it should be noted that the projects' experimental nature and methodology development related to Digital Deconstruction were time-consuming so the associated work hours could be significantly reduced if the approach were implemented on a larger scale. For instance, in the Lomme project, Vilogia's teams held bi-monthly meetings for "time spent on scheduling," and the European nature of the project contributed to additional hours, which could be minimized in future projects.

During a workshop organised during the project, the costliest steps in a deconstruction project identified by the participants were:

- Dismantling and Hazardous material
- Reconditioning and evacuation of wastes
    - Elimination / landfill
    - Recycling
    - Reuse
    - Reuse on site
- Storage
- Reuse studies
    - Inventory
    - Analyses of needs and destinations
    - Tenders' documents / prescriptions
    - LCA
- Transportation

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It is interesting to see that the participants have indicated the storage phase as relatively important in the global costs whereas it is never the case in the 3 pilots analysed, because either storage space was available on site or paid by the purchasers of the materials or, for Gare du Nord project, the cost of renting a container to store materials remains relatively low (1 600€ for 2 containers of $20m^3$).

3.3. Identification of materials with the greatest financial benefits

The cost of materials depends on market conditions. During the execution of construction projects, the value of different materials can vary significantly. For instance, stones might fetch a higher price in the market, making them valuable, while bricks may not have as much value.

In the context of deconstruction and material reuse, understanding the market value of materials is essential. It can influence decisions regarding which materials to prioritize for resale or recycling and can impact the overall financial viability of a circular deconstruction project.

We attempted to establish an average price per reused material for materials present in several projects at once, but it turned out to be unfeasible due to their significant differences from one project to another (format, condition, type of treatment, valorization method…). For instance, the average price of parquet in the Ettelbruck project is 625 € per tonne, while in the Gare du Nord project, it is 1,784 € per tonne. This variation can be attributed to the fact that the parquet in the Gare du Nord project is solid oak and required delicate deconstruction for reuse, whereas the parquet in Ettelbruck was only used for energy recovery. The prices for stones show a relatively similar average between the Gare du Nord and Ettelbruck projects at 329 € per tonne and 289 € per tonne, respectively. However, due to the substantially different contexts of the two projects, this information is insufficient to determine a reliable average price per tonne for facade stone.

So, each project's unique characteristics and the diverse treatment approaches for different materials highlight the importance of conducting individual assessments for material valuation.

3.4. Highlighting the additional costs associated with reuse

To move from the financial and economic impacts of the pilot projects to a more general understanding of the costs and benefits of the Digital Deconstruction approach, the analysis will compare the real Digital Deconstruction scenario with a fictitious scenario of demolition of the pilot building without reuse. Indeed, even if some architectural projects exceptionally propose subjects of reuse during the demolition of the building, nowadays most of the projects in North West Europe proceed to a classic demolition with a landfill of the waste sorted according to the regulatory flows.

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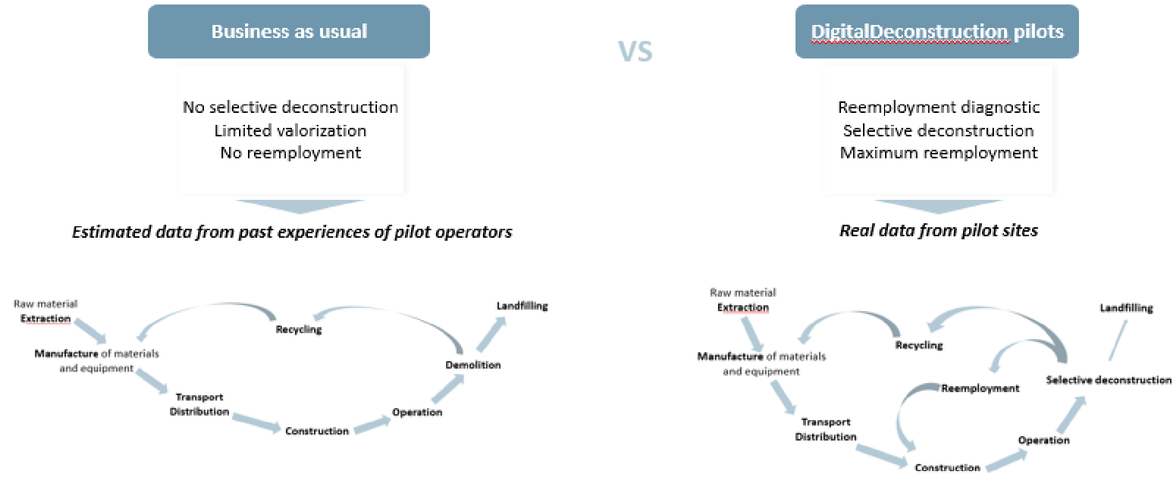

The additional cost can then be summarized in the table below:

Pilot	Business as usual	Selective deconstruction	
Gare du Nord	810 960 €	904 540 €	+ 12 % extra costs
Ettelbruck station	578 500 €	682 000 €	+ 18 % extra costs
Lomme	29 660 €	36 920 €	+ 24 % extra costs

3.5. Good practices from the pilots to reduce costs

The analysis of the pilot projects and discussions with experts held throughout the project have revealed several best practices that help reduce project costs:

- In-situ reuse projects are to be encouraged: Projects focusing on in-situ material reuse tend to be more cost-effective than those involving ex-situ reuse. Keeping materials on-site for reuse reduces transportation and handling expenses, contributing to overall cost savings.
- Implementation of 3D Scanning: Using 3D scanning technology reduces the time required for material inventory, leading to time savings and cost reduction. The efficient data capture and processing provided by 3D scanning enhance the accuracy and speed of material identification.
- Asbestos Impact: Projects containing asbestos are notably less financially viable. The presence of asbestos, as in Lomme project, limits the potential for material reuse and resale leading to reduced financial benefits. Therefore, it is crucial to conduct asbestos and hazardous material assessments before embarking on a selective deconstruction project.

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- Type of materials: Projects with few different materials and present in large volumes have generally lower costs per square meter. Indeed, the economies of scale often lead to more cost-efficient operations. Therefore, careful planning and resource allocation are essential for complicated projects involving many different materials and small volumes to optimize cost-effectiveness.
- Local context: it is essential to consider the local context of each project, especially the availability of competent companies specializing in material reuse. In areas where there are few such specialized businesses, making smaller batches to allow small deconstruction companies to respond to the market. While this may lead to slightly higher costs, it serves as an effective leverage to facilitate the achievement of material valorisation objectives. It becomes even more interesting when it involves competent local businesses, the overall effect of achieving material valorisation goals can be maximized, resulting in long-term benefits for the local economy.

By incorporating these best practices and lessons learned from the pilot projects, future deconstruction projects can be better planned and executed to achieve greater financial efficiency and sustainable outcomes.

4. Environmental Impact – « Material inventory »

These pilot projects should not only be studied in a financial approach. The implementation of circular strategies offers first and foremost environmental and social benefits, such as the avoidance of carbon emissions with reused, the diminution of waste in landfill and the generation of local jobs. In this study, we will focus only on the environmental impact. The object of this part is to determine, what are the main environmental benefits.

From a general point of view, it is first essential to consider the specific characteristics and condition of each material to determine the most suitable approach, whether it is reuse, recycling, or proper disposal, ensuring compliance with environmental regulations and safety standards.

4.1. Comparison of environnemental impact of pilots projets in DDC

First, as explained in the deliverable 4.4, there are not enough project to establish an average percentage of material reuse achieved through Digital Deconstruction, as it heavily depends on the specific context and characteristics of the deconstructed building. However, it is indeed possible to identify certain building types and key factors that can foster a high percentage of material reuse while keeping the additional costs reasonable. In this part, we will compare the environmental impact of the 3 pilot projects that were studied in the deliverable 4.4: Ettlebruck Train Station, Lomme and Gare du Nord. For these 3 projects, we were able to determine the amount of material reused. Nevertheless, due to the quality and the quantity of data, the carbon study was only realized on the most documented project: Ettlebruck Train Station.

4.1.1 Resources

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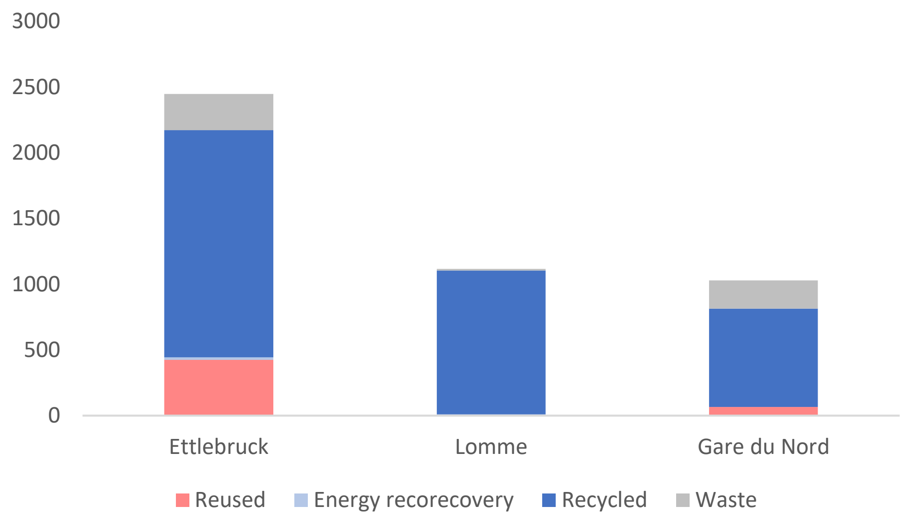
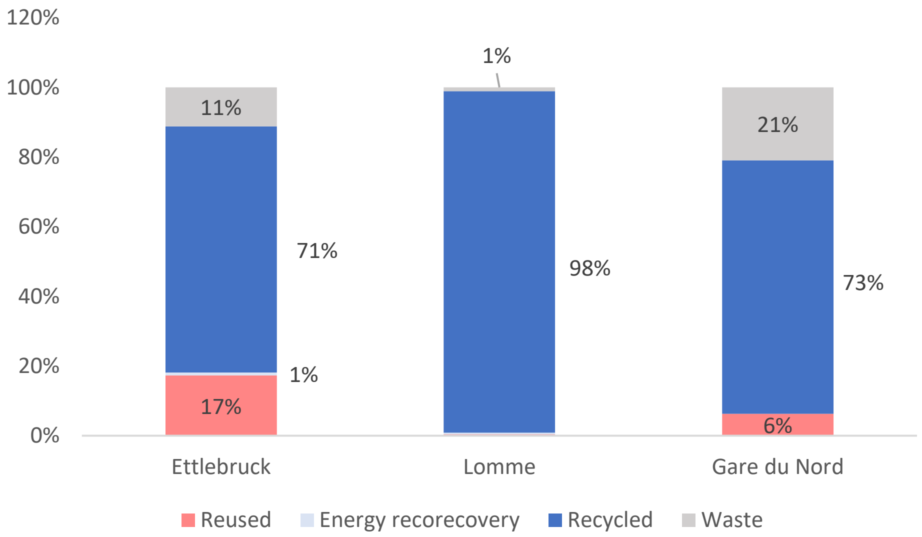
The objective of the analysis is to determine which pilot project has the better impact in terms of resources. Reuse represents benefits in terms of resources because it mostly prevents to extract and process new materials for new project of construction and renovation. However, it does not really change the end of life of the materials, the end of life will eventually take place but much later.



Tonnage by type of end of life for each project



Relative repartitions of end of life for each project

The pilot project of Ettlebruck has the best results with only 11% of the materials going to landfill, 17% of them being reused and 71% being recycled. To compare, the materials of the project of Gare du Nord, are being recycled at 73%, only 6% are being reused and 21% are going to landfill. The pilot

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project of Lomme is the less performant with less than 1% of the material being reused, nevertheless, almost all the material are being recycled.

To bring these data back to a frequently used indicator, it is possible to calculate the quantity of reused materials in each project per square meters.

	Surface (m^2)	Reused tonnage (T)	T reused /m^2
Ettlebruck	3220	424	0,132
Lomme	1000	5,4	0,006
Gare du Nord	971	67	0,067

For Lomme, the low ratio of ton reused per square meter is based on predictive study and can be partly explain by the presence of asbestos and the lack of elements qualitative enough to be reused. In the Gare du Nord pilot project, the lower results could be explained by the less important quantity of stones that have been reused, compared to Ettlebruck. Also in the case of Gare du Nord, it was a deconstruction of an Hausmannian buildings, with less heavy materials such as metals than in the train station of Ettlebruck.

4.1.2 Carbon

To put forward reuse, the French regulation RE2020 considers that materials reused are accounted as having zero carbon weight in their life cycle assessment (LCA). It is not entirely true, because to reuse materials, some operations are still required such as freight, construction, and maintenance of products, but it prevents some operations such as the phases A1 to A3 of LCA (i.e., Raw material supply, Transport and Manufacturing), because materials have already been produced. As explained before, we have not considered that reuse allows to avoid the end-of-life phases of material (phases C1 to C4), it only it delays them over time, which remains interesting in fine.

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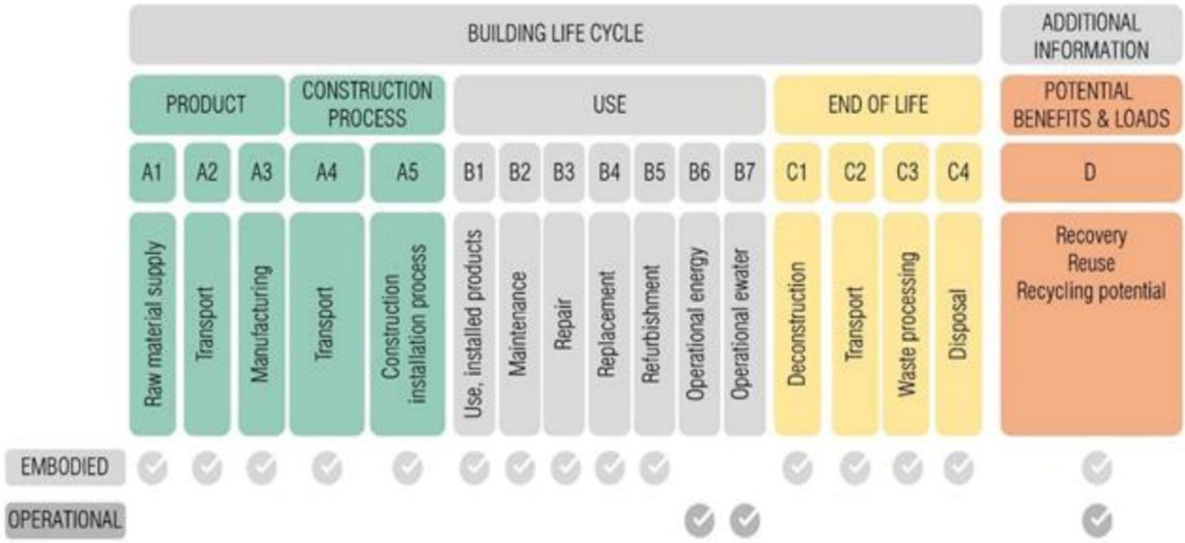

Assessment of the Building Life Cycle

That is why, to calculate the benefit of reuse in our approach, only the upstream part of the emission factor was removed: A1 to A3. To give a second life for a material or an equipment, the steps of use and construction are required. The carbon impact of the end of life is not deleted because it will occur later.

Because of the lack of data in most of pilot projects, the analysis of the carbon impact was only realized on the project of Ettlebruck. In this pilot project, we also removed the part A4 of the emission factor given on the French database "Base Inies", associated to the freight of manufactured material to the construction, of the emission factors. Instead, we use the real physical data provided by Schröder and Associate (km travelled and tonnage) for this phase.

With this study, we were not able to have generic conclusion for all type of materials. However, the methodology developed to study the carbon impact of reuse could be implement on each project of circular economy and to determine whether reuse presents benefits on a carbon point of view.

In the LCA's description above, most of the steps are calculated with averages given by actors of the construction sector and depend on the use of the building. That is why, for our study, we have chosen the following postulate:

- Emissions generated by phases A1 to A3 for each material reused are "avoided" and will be referred as "avoided emissions" bellow.
- Emissions generated by based A5 to C4 will be considered as unchanged by the process of reuse.
- The step A4 represents, in DDC scenario, the freight of deconstructed materials in order to be reuse. In our study, this step is the most variable parameter and the easiest one to change for construction enterprise and project manager. That is why our analysis is based on this parameter bellow.

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The purpose of the analysis is to determinate from how many kilometers, the impact of freight is higher than the benefit of reuse. The equation to determine this distance is the following:

Avoided emissions (in kgCO2e) * 1000 = Tons reused (t) * EF for freight (kgCO2e/t.km) * X (in km)

For example, the reused of 23 tons of canopy poles avoided 47 tCO_2e.
The emission factor for freight is the same in the whole study: 0,24 $kgCO_2e$/t.km. With these data, the distance from which reuse is not relevant in terms of Carbon is 8583 km.

The calculations and specific results for the Ettlebruck project are described in the deliverable 4.4.

One of the conclusions drawn from this project is that all the materials are not always relevant to be reused in terms of carbon. For materials from natural origin that don't require lot of treatments such as natural stones and wood, the distance should not exceed 500km and for some even 50km. For others, such as metals or glass, that required lot of energy to be processed, the distance to reuse them can be longer, more than 8000 km. To have precise results, the study should be done for each material. But this study only considerer the carbon impact of these materials, there are more consideration to it, such as biodiversity, pollution, etc.

To go further regarding the avoided emissions linked to reuse of materials: https://www.materialepyramiden.dk/

4.2. Highlighting the additional environmental benefit associated with reuse

In the same way as the financial study, we could also compare the real Digital Deconstruction scenario with a fictitious scenario of demolition of the pilot building without reuse, called BAU for the following pilot projects: Lomme and Ettlebruck. No data were collected about the classic scenario of deconstruction, regarding the material for Gare du Nord.

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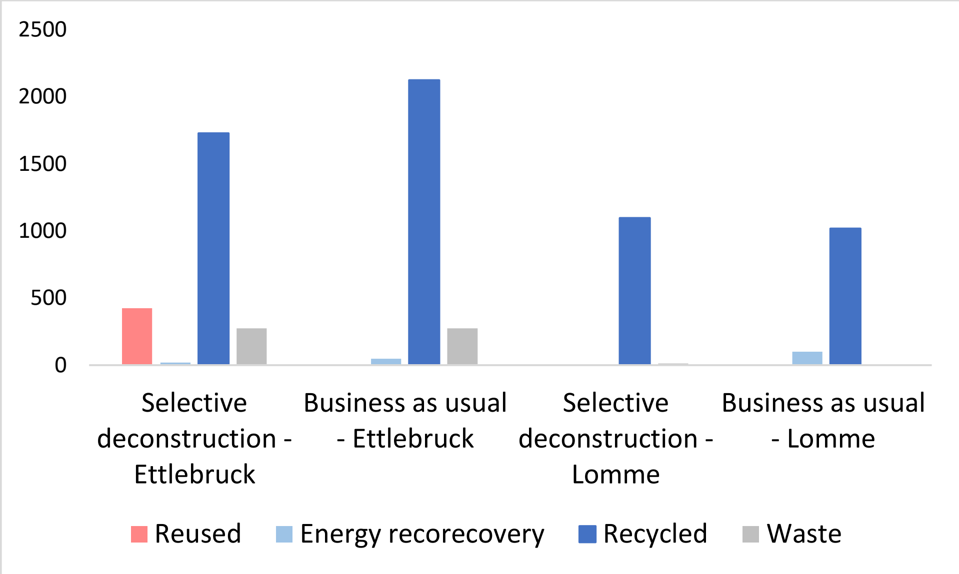

In the Ettlebruck pilot project, the implementation of circular strategy didn't change the proportion of waste going to landfill but it reduced the amount of recycled materials, being replaced by reused one. Reuse is a better outlet than recycled because it prevents from downcycling and consume less energy.

In Lomme, it is quite the opposite, because the deconstruction is done selectively, it allows more materials to be recycled, even if the amount of materials reused is very low.

5. Other benefits of circular deconstruction to take into account

5.1. Financial co-benefits

As described above, the implementation of circular strategy in a deconstruction project is usually more expensive than a classic demolition. However, the development of circular strategy with reuse presents few counterparties that were not taken into consideration in the project cost analysis. In a cost-benefit analysis, it is important to visualize the effects on society and not to stop at the direct economic impact: include and try to monetarise saved CO_2 emissions, waste of scarce raw materials, energy use and other co-benefices…

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First, to dispose waste, enterprises must pay a contribution to landfill. For ordinary industrial waste, the cost per ton[1] in France is from 165€/ton. In the pilot project of Ettlebruck, with the material reused, it could represent a saving of approximately 70 000 €.

Also, in a world where states wish to respect the Paris Agreement: contain the global warming to 1,5°C or well below 2°C and achieve carbon neutrality by 2050, and in which states ambitions to date are insufficient, it could be possible in the near future that the carbon tax become generalized to more sectors. For now on, the carbon tax concerns the consumption of fossil fuels (gasoline, diesel, natural gas), some other mechanisms on the carbon market are being used for emitting sector such as cement productors. According to numerous studies, this tax could reach 100€/tCO_2e by 2030. By reducing the carbon footprint of delivered buildings, it could represent a decrease of the tax. For example, in Ettlebruck pilot project, 57 tCO_2e are avoided, which could represent a reduction of 57 000 € in 2030.

In the same way, the handbook on circular deconstruction, written by Dr. S. Duindam and linked to the subjects developed in DDC project, explains that the economic balance of a circular deconstruction project, compared to a traditional demolition project can be achieved only if we integrate the revenues in the equation. He therefore worked on a social cost-benefit analysis that showcase how the system can bring value to the extent of its functionality. Here are the main outputs of his work:

Within the methodology of Circular Demolition, two equations are central, distinguishing between classical demolition and circular demolition or dismantling. The equations are written down in terms of costs and benefits:

$$K = O + S_k + D_k - M_k$$

$$C = O + I + S_c + D_c + R - M_c$$

Where the letters stand for the following aspects of the demolition and/or dismantling process:

- K = The costs and benefits of the classical method of demolition
- C = the costs and benefits of the circular method of dismantling
- O = the organizational costs of the demolition and/or dismantling process
- S_k = the costs of the classical services of a demolition company

[1] https://www.ecodrop.net/prix-tarifs-dechetteries-ile-defrance/#:~:text=Le%20DIB%20(D%C3%A9chets%20Industriels%20Banals,de%2065%20%E2%82%AC%20la%20tonne

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- M_k = the proceeds of materials from a classical demolition process
- I = the cost of inventorying and recording the materials in a building with a materials passport
- S_c = the cost of the circular services of a demolition company
- D_c = the cost of disposing or depositing materials that no longer have value and storing for reuse the materials that still have value.
- R = the cost of processing the materials released from a building into new use materials
- M_c = the return of materials from a circular demolition process.

The purpose of the social cost-benefit analysis is first to determine what exactly the above variables embrace in a specific situation. And which aspects can ensure that the additional efforts in a circular process also result in additional benefits, so that the K > C, or in other words to the situation where the costs of the classic demolition process are higher than those of the circular demolition/dismantling process. Or described the other way around, when a circular demolition process adds value, on which an organization can determine its strategy as an organization and in terms of building, land, and materials. If the strategy is clear, then it is also easier to initiate the long-term investments in circular demolition and to use the tools that go with it.

The methodological explanation is therefore a basic framework, within which the use of tools relating to Circular Demolition can be placed, because without a clear purpose the added value of these tools and all its functionalities cannot be properly tested. You do not know what you are evaluating it for.

To simplify the analysis, we have assumed that in the classical scenario there is only cost, and the material yield can be set to 0. In addition, we have assumed that the organizational costs of both processes are equal, even though the knowledge deficit about circular demolition/disassembly will still temporarily cause differences in these organizational costs. In a break-even analysis, the combination of equations 1 and 2 then looks like this:

$$M_c = I + (S_c - S_k) + (D_c - D_k + R)$$

This equation states that if the material revenue is equal to the cost of inventory I, the additional cost of service of the demolition/dismantling company and the additional cost of deposit, processing and storage of the materials, circular and classical demolition have the same outcome in terms of costs and benefits.

5.2. Co-benefits of circular dismantling: local job creation and health

In addition to the environmental impacts, the implementation of a circular deconstruction strategy and the maximization of material reuse also contribute to job creation at the local level, particularly

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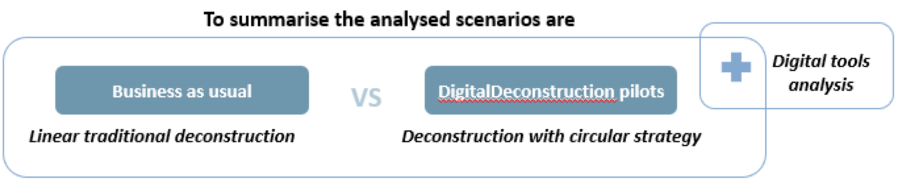
within the social and solidarity economy sectors. Indeed, circular deconstruction practices often require skilled and specialized labor to carefully dismantle and salvage materials for reuse. This demand for skilled workers can lead to the creation of employment opportunities for local communities, supporting the growth of the green economy. For instance, the Ettelbruck project has created around 480 days of work (including different type of job profiles (technician, builder, architect, engineer…).

When it is difficult to find companies specialising in reuse, one possible solution is to turn to companies specialising in heritage restoration.

Finally, Circular deconstruction practices prioritize the identification and proper disposal of hazardous materials, ensuring that they do not pose health hazards in the future. By responsibly managing and handling these materials, the risks of exposure to harmful substances are minimized, creating a healthier living, and working environments for all.

6. Focus on the impact of the digital tools

Originally, it was planned to integrate the evaluation of the impacts of the digital tools on the elaboration of a deconstruction and reuse strategy into the overall analysis conducted on pilot projects. However, due to the changes in the timeline of the DDC project and the multiple problem encountered in the collection of exploitable data, it was decided to do the following separation between the scenarios and the digital tools:



6.1. Cost of the digital tools

Estimating the cost of digital tools is a complex task because of the experimental dimension of the project. Indeed, given that the project brought together the development phases of certain tools, some of which were already relatively advanced, such as 3D scanning, while others were at a very early stage, such as R-BIM, the materials passport and the final platform designed to centralise everything.

As the tools are generally still under development, it is difficult to separate the time spent creating and testing the tools on a concrete situation, for R&D purposes, from the estimated time to be spent on a future project.

There are 2 types of cost involved in using digital tools in a deconstruction strategy. Firstly, human costs, which include the time spent by operators in collecting, processing and analysing data using the tool. Secondly, there are the machine costs, which include the costs of the servers hosting the data,

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calculation costs, etc. All these costs are detailed in deliverable *D.LT.1.1 - Detailed Business Model Prototype.*

Scan 3D

In the case of 3D scanning, a tool that is already operational prior to the project, it is interesting to note that the costs incurred are mainly linked to the surface area of the buildings, as most of the costs are associated with the human time spent by the expert in charge of taking the image on site using the appropriate equipment. The human costs associated with processing the information gathered are limited thanks to automation and the use of tools based on artificial intelligence to categorise the POIs targeted. In addition, the costs associated with data hosting and use are also limited thanks to the low computing power required and optimised storage systems.

Thus, the cost of carrying out a 3D scan to feed the selective deconstruction strategy is almost proportional to the surface area of the buildings to be deconstructed, although the structural and architectural complexity plays a significant additional role.

However, it is also important to note that the use of a 3D Scan can be particularly relevant in the case of very similar buildings within the same project. Indeed, the use of a 3D scan on one of the houses in the pilot project run by Vilogia in the north of France provided invaluable information on the inventory, while limiting costs, as it was not relevant to carry out the same scan on the 15 other houses in the batch.

Other digital tools

The analysis of costs for the other digital tools developed and used throughout the project is not as easy as for the 3D Scan, in particular because the development was not as advanced upstream of the project.

For both the tools developed by CIRDAX (materials passport and blockchain) and the R-BIM tool developed by GTB-Lab, the highly experimental nature of the Agreement Form makes it difficult to assess the relevance of the tools and their costs. During the various diagnostic and deconstruction phases of the projects, numerous exchanges took place between the project owners and the tool developers. In addition, the tools were made available to users free of charge, so that they could obtain feedback on the interfaces and their use. This logic of continuous improvement therefore generated significant costs due to the amount of time spent by the developers. Similarly, the automation of tasks and processing observed for the 3D Scan, thanks to its development prior to the project, is not yet present for the other tools, which also results in a significant volume of hours spent by the module developers (in the case of R-BIM, for example, the manual analysis of the potential for re-use and re-utilization of the materials identified is time-consuming and generates a potential additional cost that should be smoothed out over time.

Finally, as a general point, it is important to note that the costs of the digital tools included in the financial analyses for the Digital Deconstruction pilot sites are not representative of reality and cannot be extrapolated to a large scale. Analysing the relevance of the tools in terms of economic issues, considering both the additional costs and the potential gains - by spending less time establishing the

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strategy or by deconstructing larger parts of the buildings, opening the way to the resale of materials and additional revenue, for example - would require a larger number of projects carried out using fully operational tools.

6.2. Environmental impact of the digital tools

The environmental impact of digital tools is an important aspect in a complete analysis of their relevance in a deconstruction strategy. Digital tools have a significant environmental impact, and the manufacturing of digital devices and the energy consumption required to power them are the main contributors. According to studies, digital equipment accounts for 47% of the sector's greenhouse gas emissions. Digital technology is responsible for 4% of global greenhouse gas emissions.

To measure the environmental impact of digital technology, we need to consider all the effects of a digital product life cycle: design, extraction and processing of raw materials, manufacture of components, assembly, transport, energy consumption during its use, and finally recycling.

However, emissions linked to digital tools are mainly due to the terminal manufacturing phase. In the case of the project, therefore, by focusing on the phases of using the tools and storing the data on the servers, it is possible to show that the greenhouse gas emissions are relatively low compared with the emissions associated with the project in general, particularly as the emissions linked to activities in the building sector make it one of the highest emitting sectors.

In the case of the tools used and developed in the Digital Deconstruction project, it is once again hard to estimate the environmental impact they induce, particularly as it is not representative of their emissions in a future more mature version of the tool.

For example, an estimation of the environmental impact of the servers used by LIST to develop and host the Digital Deconstruction platform centralising all tools is developed below, based on this methodology :

LIST's virtual machine system has 2 CPUs and uses no GPU. If we assume an average server CPU, it uses approx. 165W at full load. Assuming a light load of 10% (high estimate, since most of the time the load is 0), we obtain the following power estimate: P = 2 * 165W/h * 0.1 = 33W/h. Cooling and other additional consumptions are taken into account via the PUE (Power Usage Effectiveness) of the datacentre, which in average sits around 2, meaning for every W of server power, the datacentre uses twice as much, and we obtain P * PUE = 2 * 33W/h = 66W/h. We then obtain a daily power of Pday = 24 * 66W/h = 1.584 kW/h. As the carbon intensity of electricity in Luxembourg is estimated at 187 gCO_2eq/kWh, we obtain an estimate of 296 gCO_2eq per day generated by the servers, with a load of 10%.

Considering a project duration of 4 years, and assuming that the servers have been running continuously throughout the project for Digital Deconstruction, we obtain an overall estimation of the emissions at 296 * 365 *4 = 432 160 gCO_2eq, meaning roughly 0.4 tCO_2eq.

Even though this result seems quite low, it is once again important to be reminded that the impact of manufacturing holds most of the global impact of the digital tools. It has to be kept in mind when considering adding more digital tools in this sector, as it will increase the need to produce more

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devices and servers, which could lead to less benefits from the deconstruction strategy in a global analysis.

6.3. Standard process for identifying whether or not it is worth using digital tools

The key phase in a deconstruction project is the preparatory phase, which is often too short, and more time should be taken to identify the context. To improve this, a manual or a website is needed to help project owners or deconstruction companies in the organisation of the different stages (processes to be carried out):

- Identification of the type of building, surface, and period of construction: make an initial macro analysis to remove from the field buildings that are too likely to be unprofitable or to present no significant reuse potential (if the probability of the presence of asbestos is too high, if the volumes are too small, if the buildings are too heterogeneous ....). A decision support table should be available in the manual/website.
- Identification of hazardous materials on site. If present, the application of the Digital Deconstruction approach will not be economically or environmentally profitable.
- Carry out a quick scan of the project to identify whether the materials are of good quality and whether they have monetary value (beware that the cost of materials changes rapidly). A decision support table should be available in the manual/website to highlight the point at which digital tools cost more than they bring in (ratio of time spent to benefits derived).
- Identification of potential sources of additional costs according to the specific characteristics of each building.
- In view of the previous analyses, carry out, or not, an R-BIM on one or all parts of the building (not necessarily needing to identify all the elements, nor to digitise everything).

Finally, use human expertise to complete the R-BIM and refine the information and prioritisations.

7. Conclusion

In conclusion of the cost-benefit analysis conducted on the pilot projects of the European program North West Europe Digital Deconstruction, we have identified key elements that illustrate the advantages and challenges of selective deconstruction and material reuse in construction.

From an environmental perspective, these projects have demonstrated the significant potential of material reuse to reduce construction waste and minimize the carbon footprint associated with the production of new materials. The valorisation of materials has also contributed to increasing recycling rates, promoting a more sustainable circular economy. In-situ reuse projects, in particular, are to be encouraged as they are generally less expensive than ex-situ projects and limit the environmental impact due to transportation. Conducting a pre-analysis of operations is essential to target projects that are likely to be profitable both economically and environmentally. Factors such as the probability of asbestos presence, small volumes, and heterogeneous buildings need to be considered, as they may influence the cost-effectiveness of selective deconstruction.

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However, on the financial front, the results have been more nuanced. While material reuse can sometimes prove to be more cost-competitive, it depends on the local context, the availability of specialized reuse companies, and the scale of the project. Larger projects tend to be more economically viable due to economies of scale.

Despite the costs associated with implementing circular deconstruction and material reuse strategies, these projects have also shown additional positive impacts. They have created local jobs, particularly in the social and solidarity economy sector, while promoting the health of future users and occupants of buildings through the responsible handling of hazardous materials.

To maximize the benefits of selective deconstruction and material reuse, it is essential to consider the local context, project scale, and develop efficient logistic strategies. It is also crucial to include objectives in the project specifications based on results, such as the percentage of material reuse in tons or monetary value, rather than prescribing specific means. This approach allows companies to adapt to the unique context of each project, ensuring both economic efficiency and environmental performance.

Finally, we have learned that integrating digital tools, despite adding an additional process, can lead to time savings and improved efficiency. For instance, utilizing 3D scanning for materials inventory can reduce the time spent on this task and subsequently lower associated costs. Additionally, digital platforms like Digital Deconstruction facilitate communication and collaboration between project owners and deconstruction companies, streamlining the process and fostering better project outcomes.

The good practices to be implemented can be summarised as follows:

1. In-situ reuse projects are to be encouraged: They are generally less expensive than ex-situ projects and limit the environmental impact due to transportation.
2. A pre-analysis of operations should be carried out to target those most likely to be profitable from both an economic and environmental point of view: If the probability of the presence of asbestos is too high, if the volumes are too small, if the buildings are too heterogeneous then selective deconstruction may not be profitable.
3. Including in the specifications objectives in terms of results (% of reuse in tons or €) and not of means is more effective: To enable companies to adapt to the context of each project and ensure environmental performance.
4. The use of digital tools even though they add an additional process, can allow to save time:
    a. The use of a 3D scanning reduces the time needed to carry out the materials inventory, which reduces the time spent and therefore the associated costs.
    b. The use of a platform as Digital Deconstruction can help to encourage exchanges between the project owners and the deconstruction companies.

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Analysing various projects and contexts can reveal patterns and strategies that contribute to successful material reuse. By identifying these key factors, project teams and stakeholders can better plan and implement sustainable deconstruction practices, leading to higher rates of material reuse. Here the analysis is based on 3 projects, to draw more interesting lessons about reuse it is important to carry out this type of study on other reuse projects to massify figures.

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