Environmental consequences of refurbishment vs. demolition and reconstruction: a comparative life cycle assessment of an Italian case study

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Abstract. In the building sector, the new standards for energy efficiency are reducing the energy consumption and the carbon emissions for building operation to nearly zero. As a result, the greenhouse gases emissions and related environmental impacts from materials production, and especially insulation, are becoming dominant. In the next future, most of building stock is expected to be refurbished and a great amount of construction materials will be consequently required. A relevant share of waste is generated from building construction and demolition and limiting the volume is a priority of the EU community. In this work the renovation of industrial buildings in a dismissed area located in Lecco, Italy, was considered as case study. Five alternative construction systems for renovating the building envelopes were assumed, and a life cycle assessment (LCA) adopted in order to measure the environmental impact of each alternative. The results where compared with a scenario which includes demolition and reconstruction of a similar building with the same net volume and thermal resistance. The results showed that timber and concrete are the most valuable materials to rebuild the structures in case of demolition, contrarily to steel which leads generally to higher environmental impacts, except land use. Refurbishment scenarios generally account for a lower global warming potential (GWP) even if demolition, waste treatment and benefit from recycling/reuse are taken into account.

1. Introduction

The construction sector and, more specifically, the building renovation sector plays a decisive role in the achievement of the European targets for the reduction of energy consumption and CO2 emissions.

More than the 75% of the European building stock has been built before 1980, i.e. before the introduction of the first energy performance regulations in several EU countries [1].

Most of them do not meet current standards and building codes so they are expected to be refurbished or demolished or deeply transformed to ensure its use over time. As a matter of fact, the maintenance and/or transformation of the existing building stock is nowadays a main concern in most European countries [2].
Very often, the owner’s perception of cost and operational advantages (or opportunities for deep transformation) leads to a preference for demolition and new construction rather than refurbishment. However, in a context of increasing attention to the impacts of buildings on the environment, it is not possible to neglect in the decision-making processes data derived from the environmental assessment of the different options. European, and consequently Italian standards, mainly address the decrease of the environmental impact during the use phase through reducing the demand for operating energy [3]. While the energy demand and resulting emissions during the use stage are decreasing, the energy needed during the production stage is increasing because of the higher material input, e.g. due to the increase of insulating materials processing increases [4]. As a matter of fact, the fossil carbon emitted by manufacturing of materials and construction might significantly affect the carbon saving from operational energy [5]. For this reason, the environmental impact of buildings should consider their whole life cycle, including the production and the end-of-life stage.

2. Objective and scope
The purpose of the work is to investigate the effect of material choice on the environmental footprint of a building under two alternative scenarios: refurbishment versus demolition and new construction.

The main objective is to demonstrate to practitioners how much the choice of the building component and their materials can be relevant for the reduction of main LCA indicators, especially climate change (GWP). In order to meet this goal, five alternative construction technologies per each scenario were compared and a LCA methodology was adopted to account for impact from material processing, transportation, onsite construction and end of life of demolition waste.

3. Case study presentation
The object of this study case is a disused industrial building complex situated in Northern Italy for which a major transformation project is planned. The complex includes three main volumes (identified as A, B, C), structured in sub-volumes, which were built during various periods between the 20’s and the 50’s of the XX century [6] and differ in shape and dimension.

The transformation project involves the demolition of volumes A1, A2b, B1a and most recent parts of the volumes B2 and C2 - which are not subject to conservation by Italian laws - and the replacement of the volumes A2b and A1.

In this framework, a Life Cycle Assessment was introduced to provide additional elements to the evaluation of design options regarding the other volumes included in Table 1 for which it is possible to consider either demolition/reconstruction or conservation.

The surfaces and volumes considered in the comparative analysis are the following (table 1):

![Figure 1. Gross area and Volume of the buildings object of the comparative analyses.](image-url)
Table 1. Gross area and Volume of the buildings object of the comparative analyses.

| Cod | Buildings | Gross Area | Volume |
|-----|-----------|------------|--------|
| A2a | 157       | 488        |        |
| B1b | 434       | 1720       |        |
| B1c | 91        | 307        |        |
| B2  | 237       | 644        |        |
| C1  | 176       | 647        |        |
| C2  | 625       | 3750       |        |
| C3  | 202       | 623        |        |

The comparison of the two alternative scenarios (refurbishment versus demolition and new construction) is limited to the building envelope considering equal built volume, gross area and thermal transmittance (U value equal to 0.180 W/m2K for roof and 0.210 W/m2K for walls as demanded by current Italian regulation for energy efficiency of buildings).

The elements of the envelope considered in the analysis include the exterior walls and roofing; flooring, doors and windows are not included as they are assumed to be replaced in both scenarios.

Five alternative solutions for the envelope insulation were considered among the most common on the Italian market:

- T1 – Expanded Polystirene (EPS) boards applied on the exterior surface of the envelope;
- T2 – Wood fiber insulation boards (WOOD) applied on the exterior surface of the envelope;
- T3 – Mineral wool panels (ROCK) applied on the exterior surface of the envelope;
- T4 – Polyurethane rigid boards (PU) applied on the exterior surface of the envelope;
- T5 – Hempcrete blocks (HEMP) applied on the exterior surface.

The demolition and new construction scenario includes into the boundaries the building reconstruction based on four alternative load-bearing structure which are combined with the five thermal insulation solutions described above. Particularly, as shown in Table 2, T1 is combined with a clay brick block structure, T2 with a CLT structure, T3 and T4 with a steel structure and T5 with a reinforced concrete frame. The structure of the roof is assumed out of CLT for T2, while a timber frame is supposed for the other solutions.

4. Methodology

4.1. Reference construction technologies as alternatives for roofs and exterior walls

Ten alternatives construction systems for building envelope were investigated, by applying the same five insulation technologies for the two alternative scenarios: five for refurbishment of external walls and roof (R_W and R_R) and five for new constructions of external walls and roof (N_W and N_R).

The functional unit (FU) is identical for all investigated alternatives and is defined as follows:

- same building size (identical net floor area and walls/roof surfaces);
- identical U-value for roof alternatives (0.18 W/m2K) and walls (0.21 W/m2K);

As shown in Table 2, for each alternative, four different elements were defined and designed: insulation, building structure, exterior finishing and interior finishing. The composition and the dimension of the different elements was adapted in order to fulfill the technical requirements and the FU.
Table 2. Alternative technological solutions for walls and roofs for the two considered alternative scenarios: refurbishment and new construction.

| Building element | Scenario          | Inv. Code | Element code | Insulation thickness (mm) | Insulation | Structure | Exterior finishing | Interior finishing |
|------------------|-------------------|-----------|--------------|---------------------------|------------|-----------|-------------------|-------------------|
| WALLS            | Refurbishment     | EPS       | R_W_EPS      | 160                       | x          | x         | x                 | x                 |
|                  |                   | WOOD      | R_W_WOO      | 180                       | x          | x         | x                 | x                 |
|                  |                   | ROCK      | R_W_ROCK     | 160                       | x          | x         | x                 | x                 |
|                  |                   | PU        | R_W_PU       | 100                       | x          | x         | x                 | x                 |
|                  |                   | HEMP      | R_W_HEMP     | 250                       | x          | x         | x                 | x                 |
|                  | New Construction  | EPS       | N_W_EPS      | 120                       | x          | x         | x                 | x                 |
|                  |                   | WOOD      | N_W_WOO      | 140                       | x          | x         | x                 | x                 |
|                  |                   | ROCK      | N_W_ROCK     | 260                       | x          | x         | x                 | x                 |
|                  |                   | PU        | N_W_PU       | 360                       | x          | x         | x                 | x                 |
|                  |                   | HEMP      | N_W_HEMP     | 260                       | x          | x         | x                 | x                 |
| ROOF             | Refurbishment     | EPS       | R_R_EPS      | 180                       | x          | x         | x                 | x                 |
|                  |                   | WOOD      | R_R_WOOL     | 180                       | x          | x         | x                 | x                 |
|                  |                   | ROCK      | R_R_ROCK     | 180                       | x          | x         | x                 | x                 |
|                  |                   | PU        | R_R_PU       | 180                       | x          | x         | x                 | x                 |
|                  |                   | HEMP      | R_R_HEMP     | 260                       | x          | x         | x                 | x                 |
|                  | New Construction  | EPS       | N_R_EPS      | 180                       | x          | x         | x                 | x                 |
|                  |                   | WOOD      | N_R_WOOL     | 140                       | x          | x         | x                 | x                 |
|                  |                   | ROCK      | N_R_ROCK     | 160                       | x          | x         | x                 | x                 |
|                  |                   | PU        | N_R_PU       | 100                       | x          | x         | x                 | x                 |
|                  |                   | HEMP      | N_R_HEMP     | 260                       | x          | x         | x                 | x                 |

For the refurbishment case (R_W, R_R), an ETICS (external thermal insulation composite system) has been adopted for each alternative technology. EPS consists of a standard ETICS, which is based on the installation of 16 cm of expanded polystyrene boards on the façade and the application of a mineral raster. In parallel, an EPS insulation is applied on the existing roof structure, which is completed with the ventilation and clay roof tiles. Similarly, WOOD, ROCK, PU and HEMP alternatives consist on the installation on the existing structures of respectively wood fiber insulation boards, mineral wool panels, polyurethane rigid boards (PU), and hempcrete blocks, both on the facades and on the existing roof.

The same insulation materials were used to design the technological alternatives for the new construction scenario (N_W and N_R). For EPS, the ETICS was applied on a new 30 cm wall out of clay blocks as well as on a timber frame pitched roof. WOOD construction technology required a new timber wall and roof solution out of cross-laminated timber (CLT) panel, on which a wood fiber insulation was installed. Both ROCK and PU alternatives required a steel framed structure on which the insulation was installed in the cavity, while for the HEMP solution a reinforced concrete frame was assumed as a main building structure and the hempcrete block used as filling for walls and external insulation for the timber frame roof.

4.2. LCA calculation model
The complete model developed for the LCA is shown in Figure 1. Products and processes were modeled with PRé Consultants - SimaPro 8.3 [7], and the database Ecoinvent 3.2 [8] was used to obtain the secondary LCI data. In case of refurbishment scenario, the impact of each material adopted in the five different alternatives where assessed through a life cycle assessment (LCA). The ReCiPe midpoint
assessment method was adopted to transform the long list of life cycle inventory results into a limited number of indicator scores [9]. All the eighteen midpoint indicators were taken into account, considering a hierarchic cultural prospective, in order to express the relative severity on an environmental impact category.

Figure 2. Schematic diagram of the adopted methodology

In parallel, the demolition scenario where modelled for those components and materials that had to be demolished and replaced by new component. All demolished materials were treated as waste according to two end of life options: landfill, for inert material with no potential, or recycling, for materials with recovery potential. Similarly as refurbishment case, all materials used for alternative new components were listed, impact assessed on the base of a LCIA and the ReCiPe midpoint method used to characterize the impacts and assess the burdens for the different environmental impact indicators. As a second step, the electricity and the fuel consumed by all the equipment used during the construction and installation phase, as well the diesel to transport the materials from manufacturing to construction site, were estimated. All the impacts accounted for construction phase were evaluated through the LCIA and burdens summed up to those calculated for materials production. Then, a full LCA were performed in order to compare the eighteen indicators for each alternative construction solution and define the best environmental friendly alternative for each scenario. Finally, the greenhouse gas (GHG) emissions were calculated and the IPCC method [10] used to measure and compare the environmental footprint of each alternative.
4.3. Boundaries of the system
The LCA model is developed according to the standard EN 15804:2012 [11]. For the refurbishment scenario, the analyses was limited on the evaluation of the module B5 (refurbishment phase), which includes internally the modules A1-3 (extraction and production of renovation materials) and modules A4-5 (construction phase). These submodules were assumed as the most relevant for the FU. Thus, all the other were considered out of the boundaries.

Contrarily, in the demolition and reconstruction scenario the modules C1-4 (end of life stage) were included in the LCA to evaluate the demolition phase of the existing building, as well as the module A1-5 for the reconstruction of the new building. The EoL stage consists of four stages. In C1-3, the building is demolished and all materials are sorted. In disposal stage C4, two different disposal scenarios, landfill and material recycling, were assumed. The disposal scenarios were considered to be independent and are never mixed. Additional benefits and loads beyond the system boundaries were not allocated to the FU but were accounted for separately in module D to measure the influence on the results.

As for the refurbishment scenario, all the submodules in stage A were included for the impact assessment of the production and installation of the new components, while module B was excluded and its impact neglected since its assessment was beyond the scope of this analysis.

The system boundaries of the products and processes along the LCA are defined according to two criteria. The first considers the second order calculation depth, which includes materials used in processing, transport and other operations. The second criterion considers the cut-off method, which define when a flow is no longer relevant to the system. By-products of the FU, such as recycled materials, are outside the system boundaries. All other waste treatments are inside the boundaries, while all beneficial impacts are outside and are accounted for separately.

Regarding the physical parts of the building, only over ground elements were taken into account in the calculation. Particularly, opaque elements for the envelope are included in the LCA, while all the transparent elements, partitions, doors and underground elements (basement floor and foundations) are excluded.

4.4. Production & construction stage (mod. A1-5)
In the production phase A1-3, the materials are modeled according to the processes included in the ecoinvent 3.2 dataset. The innovative products, e.g. hempcrete blocks used in HEMP, were modeled according to the inventory defined by Arrigoni et al. [12]. Other non-conventional materials were created from the ecoinvent primary data by adopting a mass allocation. All the materials were assumed to be installed on site, except for WOOD in new construction scenario where partially off site activities were expected for CLT manufacturing, and the impacts were assessed in sub-modules A2-3. Specifically, 59 kg/m² of CLT was manufactured in WOOD both for walls and for roof. Post-production activities as drilling cutting and moving required 3.4·10^3 kg of heavy industrial machinery and 2.7 kWh of medium-voltage electricity. The energy mix from Italy was assumed.

All the main construction activities expected during the construction phase for the two alternative scenarios were considered in module A4-5, including the vehicles involved for the material transportation and equipment used by construction workers to install the materials needed to refurbish the building. In case of refurbishment scenario, only a small part of the building were demolished, essentially the damaged timber elements of the existing roof, which required a disposal and a local substitution with new timber elements. The duration of that activity is limited to one week and all the replaced structural materials were supposed to be disposed in the closest landfill, 17 km far from the site. For each alternative included in the analysis, a 16-32 metric ton truck, EURO3, was considered for the transportation processes in sub-module A4, assuming a conventional distance of 50 km between material suppliers and construction site.

According to the demolition and reconstruction scenario, a large amount of material from demolition is expected to be wasted and transported to waste treatment centers. This activities was expected to require almost 6 weeks with many heavy machines for excavation and material movement. As for
refurbishment case, the same conventional distances were assumed for material transportation to final disposal and from suppliers to the site.

For each scenario, all the interior and exterior finishing were supposed to be installed on-site, requiring 65.4 kJ of diesel for the building machinery in sub-module A5.

4.5. **End of life scenarios of demolition waste (mod. C)**

At the end of life (EoL), three different waste treatments were assumed:

- inert landfill: considered for materials that do not release hazardous substances after building deconstruction. Normally, this waste treatment includes demolition materials with no GHG emissions into the air;
- sanitary landfill: considered as temporary storage for reactive materials as biogenic products which cannot be recycled due to the presence of phenolic glue. Often impacts from this waste treatment is significantly high since organic materials normally release a large amount of CH4 during their decay;
- recycling: consists of generating new products from waste materials. The recycling of most construction products is limited to a down-cycle process, which leads to a lower value than that of the virgin material.

From the combinations of different waste treatments for each material, two alternative disposal scenarios were defined:
1. landfill;
2. recycling.

The modules C1-3 are modeled as a single process including demolition, transportation and sorting.

In landfill scenario, all non-biogenic materials are assumed to be landfilled, while bio-based products are temporarily transferred to the sanitary landfill.

In recycling scenario, waste materials from wood and potential recycling categories are assumed to be fully recycled. All solid wooden products are assumed to be recycled in a down-cycling process to produce wood chips. Wood chips are a co-product generated from sawn residues, and the impact allocated is generally low [13]. In contrast, steel bars used in reinforced concrete, assumed as 1% of the volume, can be fully recycled in an up-cycle process, which leads to a high benefit [14]. A down-cycling process for recycled aggregates production was assumed for concrete.

For each scenario, 100% effectiveness is assumed. Thus, material losses that can occur and lead to residual waste, among other effects, are neglected. Almost 97% of the waste material is inert, of which 75.6% with no potential for material recovery.

4.6. **Loads and benefits beyond the system boundaries (mod. D)**

All the loads and benefits from avoided processes and avoided materials that are beyond the boundaries are separately accounted for in module D. In recycling scenario all the benefits from materials recycling are accounted for as avoided extraction and production of virgin materials.

In this study, all the beneficial effects of waste treatment are allocated to products according to the mass allocation method.

5. **Results**

5.1. **LCA Comparison of construction alternatives**

In this section, the results from the life cycle assessment of the different construction alternatives are presented and discussed. Impacts from roof and walls production and construction as well as from EoL of demolition waste are aggregated and normalized. Figure 3 shows the impact of each refurbishment alternative. In general, EPS, WOOD and HEMP accounted for the highest scores, both in terms of burdens on the ecosystems and on depletion of resources. In particular, EPS accounts for the lowest mass, since the specific density of the synthetic ETICS is much lower than other alternatives.
Nevertheless, the specific impact from A1-3 per mass of product is much higher than the others, and definitely results in a higher impact, particularly on air pollution.

![Environmental Impacts for Five Alternative Construction Systems](image.png)

**Figure 3.** Environmental impacts for five alternative construction systems, calculated for the refurbishment scenario according to the ReCiPe method.

The two best performing alternative refurbishment solutions for the refurbishment scenario result PU and ROCK, where a specific impact per mass of allocated product is relatively low and the mass involved in the ETICS, especially in PU, is much lower than the others.

A larger variation of the results is shown in Figure 4, where the five different alternative solutions for new construction are compared.
Figure 4. Environmental impacts for five alternative construction systems, calculated for the new construction scenario according to the ReCiPe method.

EPS accounted for the higher score for the Global Warming indicator, while for the other air impact categories a lower score was registered. ROCK accounted for the largest air impact score, while the impact on water ecosystems sensibly decreases. Impacts from PU is generally high due to the influence of the steel substructure needed for the walls assembly. Finally, the two biobased solutions, WOOD and HEMP, accounted for the lowest environmental impacts, and are able to reduce by 60-95% the environmental loads, except the land use category due to the nature of the biogenic materials which require space for growing and harvesting.

5.2. Carbon footprint assessment of the construction alternatives

Finally, the ten construction alternatives, five for refurbishment and five for new construction, where compared in order to show the magnitude of impact variation. For this comparison, only the Global Warming Potential, expressed as kilogram of CO$_2$-eq per m$^2$ of net floor area, and results, subdivided per modules, are shown in Figure 4.
Figure 5. Comparison of the Global Warming Potential of the ten alternative construction systems, calculated through the IPCC 2013 method. According to EN 15804, Mod. A1-A5 states for production & construction, Mod. C for demolition & waste treatment, and Mod. D for benefits & loads beyond the system boundaries.

Specifically to Global Warming, new construction option showed a higher impact compared to refurbishment for each construction alternative. Biobased solution resulted as the most environmental friendly solutions essentially due to the low GHG emission from processing materials. Negative impacts accounted for in module D lead to an additional reduction of the carbon footprint, which bring the technologies in line with refurbishment options. Only avoided emissions from virgin materials extraction is taken into account in module D. The biogenic CO2 storage in biobased products during the building service life (module B) was excluded from the system boundaries.

No relevant impact variation was registered for the refurbishment alternatives. Among the five options, EPS accounted for a slightly higher carbon emissions. Following the two biobased solutions, which are able to save 3-5% of GHG emissions for material production, ROCK, with 20% saving potential, and finally PU, which was able to save up to 33% of carbon emissions.

6. Conclusions and discussion
The choice of material for insulating the building envelope plays a fundamental role in limiting the environmental footprint of the two selected scenarios, refurbishment versus demolition and reconstruction. In case of refurbishment (R), considering the case study under analysis, the lightweight rigid materials can be applied directly on the existing building surface and a significant amount of material can be saved. Thus, polyurethane (PU) is the technological construction choice that accounts for the lowest global environmental impact, able to save roughly 33% of carbon emission if compared to standard ETICS solution (EPS). The two bio-based alternatives, fibre wood (WOOD) and hempcrete blocks (HEMP) have a higher density compared to synthetic insulation and even if the specific impact per kilogram of product is generally low, more insulation per m² is required to achieve the same functional unit (FU). A higher dispersion of results was obtained for new construction (N), where five alternative construction technologies were compared. For this scenario, the influence of the structure and demolition of existing building considerably affects the global results, contributing to increase the impact per FU. Synthetic insulation materials, such as EPS and PU, which are applied on massive system (masonry), account for the highest impacts. Contrarily to refurbishment, bio-based materials, such as WOOD and HEMP, accounted for the lowest environmental impact, except for the land use indicator where the highest value was measured. If only GWP indicator is considered, even taking into account
the benefit from energy and material recovery from demolition waste (module D), refurbishment can be always considered the best environmental friendly alternative. Additional benefit from temporary carbon storage can be expected if biogenic CO$_2$ would be included in the calculation. A more specific method to include the contribution of storing carbon and delay the release of biogenic CO$_2$ in the atmosphere should be included in future studies, as well as effect of repair and replacement of exhausted component during the service life and end of life.

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