ENVIRONMENTAL CONSEQUENCES OF REFURBISHMENT VERSUS DEMOLITION AND RECONSTRUCTION: A COMPARATIVE LIFE CYCLE ASSESSMENT OF AN ITALIAN CASE STUDY

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ABSTRACT

In the building sector, 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 gas emissions and related environmental impacts from materials production, and especially insulation, are becoming key factors. In the near future, most of the 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 a case study. Five alternative construction systems (EPS, WOOD, ROCK, PU, HEMP) 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 were compared with a scenario which included 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 environmentally friendly materials to rebuild the structures in case of demolition, contrary to steel which leads generally to higher environmental impacts, except land use. In general, EPS, WOOD and HEMP technological alternatives accounted for the highest scores, both in terms of burdens on the ecosystems and on depletion of resources, while ROCK accounted for the lowest scores. Finally, refurbishment scenarios generally accounted for a lower global warming potential (GWP) even if demolition, waste treatment and the benefit from recycling/reuse are taken into account.

KEYWORDS

refurbishment, demolition, reconstruction, LCA, construction materials

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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 CO_2 emissions.

More than 75% of the European building stock was built before 1980, i.e. before the introduction of the first energy performance regulations in several EU countries (Häkkinen 2012).

Most of those buildings do not meet current standards and building codes, therefore they are expected to be refurbished or demolished and rebuilt to ensure their use over time. As a matter of fact, the maintenance and/or transformation of the existing building stock is now a main concern in most European countries (Alba-Rodríguez et al. 2017).

Often the owner's perception of cost and operational advantages (or opportunities for deep transformation) leads to giving preference to 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 (Sartori and Hestnes 2007). 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 (Blengini and Di Carlo 2010). As a matter of fact, the fossil carbon emitted by manufacturing of materials and construction might definitely vanish the benefit from carbon saving from operational energy (Rovers 2014). For this reason, the environmental impact of buildings should consider their whole life cycle, including the production and the end-of-life stage.

2. STATE OF THE ART

The methodology of life cycle assessment (LCA) has been introduced in the building sector since the early 1990's and can be applied to decision making to improve the environmental performance of buildings (Tillman 2000).

Most studies related to the assessment of different strategies of intervention on the existing building stock have used a LCA methodology mainly focused on the evaluation of the building before and after energy retrofitting (Vilches et al. 2017). The comparison from the point of view of environmental impact, in demolishing existing buildings versus constructing new buildings, is not always systematically addressed in the literature. Some studies (Lima Gaspar and Santos 2015; Weiler et al. 2017) reveal that building refurbishment is a more sustainable strategy than new construction as it represented a lower material intensity and embodied energy consumption and less demolition waste. The environmental impact of life cycle extension through renovation in most cases is lower than demolition and new construction, although in practice (up to now) the higher energy performance of new construction after demolition reduces the differences (Thomsen and Van Der Flier 2010). In other studies, assuming the energy performances of the refurbished and the rebuilt options as equal, the material input and the construction phase represent the highest impacts. In addition, if the impacts of the demolition of the existing building and the demolition at the end of the life of the new building are summed up, the impact of the demolition phase definitely becomes much higher compared to the refurbishment option (Marique and Rossi 2018).

But differences in values among case studies may occur caused by different climatic conditions or building contexts, e.g. where construction or demolition works tend to be difficult, or the kind of building materials used.

For this reason, the debate about the environmental impact of interventions in the existing building stock is still open and the conclusions are related to specific cases.

3. 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.

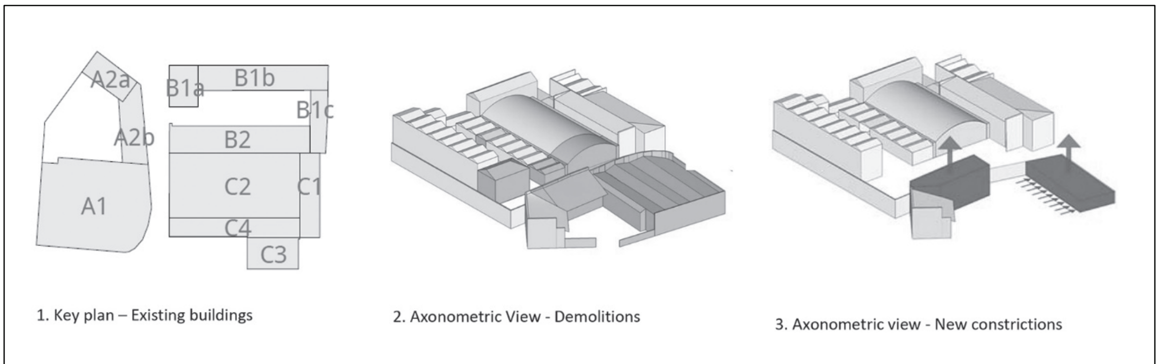
The main objective is to demonstrate to practitioners how relevant the choice of the building components and their materials can be relevant for the reduction of main LCA indicators, especially climate change (GWP) can be. In order to meet this goal, five alternative construction technologies per each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

4. CASE STUDY PRESENTATION

The object of this case study 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 20th Century and differ in shape and dimension. The result of this stratified construction is a very heterogeneous area that is made up as follows:

- small buildings dated at the beginning of the Nineteenth Century built as residences (B1a, C1) or storehouses (A2a, A2b, C3) built with masonry wall in bricks and stone, reinforced concrete and hollow block floors, pitched roofing in wood;
- shed type buildings dated between 1930 and 1950 used for workshops and laboratories (B1b, B2) built with walls in bricks and stone, with vaulted roofing in steel reinforced bricks or pitched roofing in wood;

FIGURE 1. Key plan with buildings code, Axonometric views of demolitions and new constrictions.



- large industrial warehouses dated around 1950 (C2 building: structure in reinforced concrete and steel reinforced bricks vault; A1 building: mixed structure masonry wall and reinforced concrete pillars, pitched roofing). On the site, there is an important restriction to building within the railway belt: it is forbidden to build, rebuild or extend buildings of any type in the 30 meters belt from the nearest rail. These restrictions to demolition and rebuilding activities affect volume A2a and part of volumes in lot B and C. The transformation project involves the demolition of volumes A1, A2b, B1a and the 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 analyses are shown in Table 1.

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/m^{2}K for roof and 0.210 W/m^{2}K for walls as demanded by current Italian regulation for the energy efficiency of buildings).

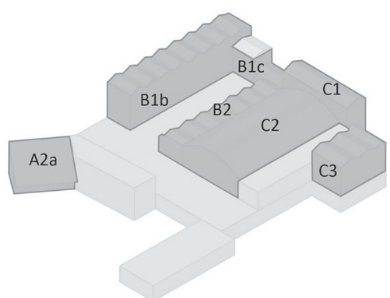
The elements of the envelope considered in the analysis include the exterior walls and roofing, flooring, doors and windows are not included as they are assumed to be replaced in both scenarios.

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

- T1—Expanded Polystyrene (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.

TABLE 1. Gross area and Volume of the buildings object of the comparative analyses.

Cod.	Buildings	*Gross Area*	*Volume*
		m^{-2}	*m^{-3}*
A2a		157	488
B1b		*434*	*1720*
B1c		*91*	*307*
B2		*237*	*644*
C1		*176*	*647*
C2		*625*	*3750*
C3		*202*	*623*



The demolition and new construction scenario include into the boundaries the building reconstruction based on four alternative load-bearing structures 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 cross-laminated timber (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.

5. METHODOLOGY

5.1 Reference construction technologies as alternatives for roofs and exterior walls

Ten alternative construction systems for the 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 construction 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/m^2K) and walls (0.21 W/m^2K);

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.

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 plaster. 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 are applied 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 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 was used as filling for walls and external insulation for the timber frame roof.

5.2 LCA calculation model

The complete model developed for the LCA is shown in Figure 2. Products and processes were modelled with PRé Consultants–SimaPro 8.3 (PRé Consultants 2016), and the database Ecoinvent 3.2 (Moreno Ruiz et al. 2015) was used to obtain the primary LCI data. In the case of the refurbishment scenario, the impact of each material adopted in the five different alternatives

TABLE 2. Alternative technological solutions for walls and roofs for the two considered alternative scenarios: refurbishment and new construction.

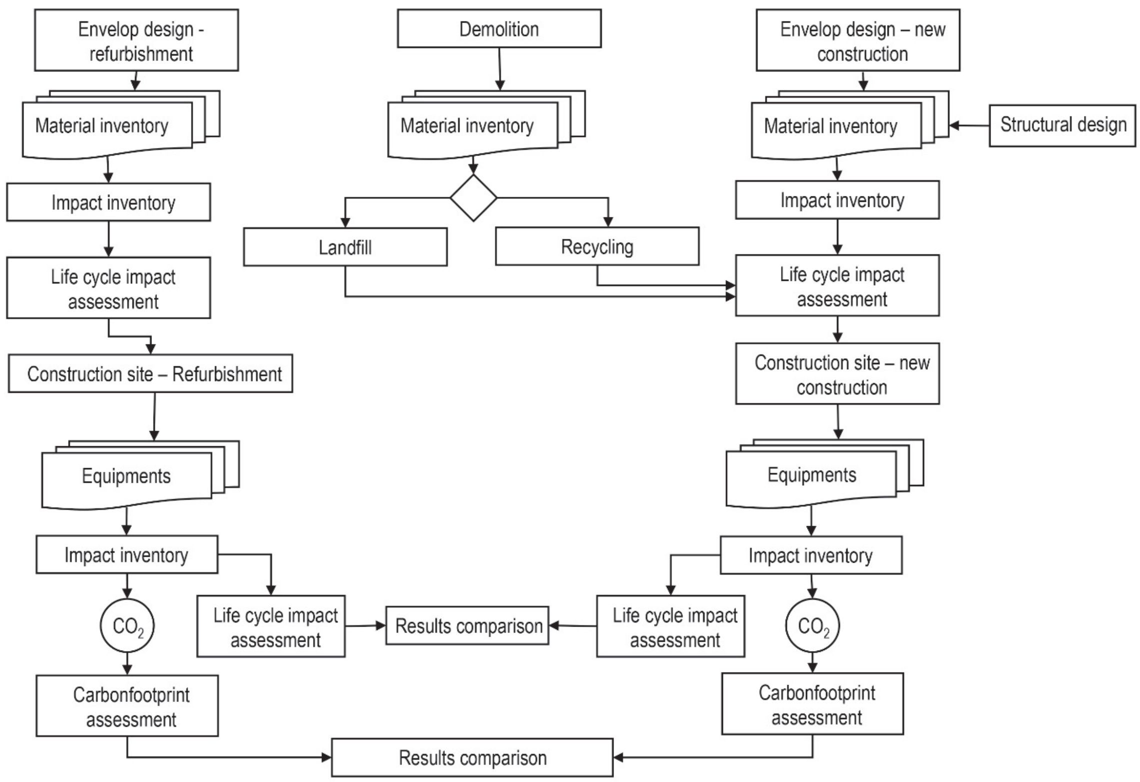
Building element	Scenario	Ins. Code	Element code	Insulation thickness (mm)	Insulation					Structure						Exterior finishing		Interior finishing				
					Polystyrene foam	Fibrewood	Stone wool	Polyurethane rigid foam	Hempcrete block	Clay bricks	CLT panels	Steel frame	Concrete Frame	Timber frame	Existing structure	Cover plaster, mineral	Clay roof tiles	Cover plaster, organic	Cover plaster, mineral	Render, mineral	Sawnwood	Existing finishing
WALLS	Refurbishment	EPS	R_W_EPS	160	x										x	x		x				
		WOOD	R_W_WOOL	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	100	x					x						x		x				
		WOOD	N_W_WOOL	120		x					x					x			x			
		ROCK	N_W_ROCK	140			x					x				x			x			
		PU	N_W_PU	80				x				x				x			x			
		HEMP	N_W_HEMP	360					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	100				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	

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 (Goedkoop et al. 2013).

All of 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.

In parallel, the demolition scenario were modelled for those components and materials that had to be demolished and replaced by a 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 for the refurbishment case, all materials used for alternative new components were listed, impact assessed on the basis 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 construction (module A5) and demolition (module C1), as well the diesel to transport the materials from manufacturing to construction site, were estimated. Furthermore, all temporary equipment, e.g. wooden formworks and scaffolds, were included in mod. A5, as well as waste production from material transportation and installation. All the impacts accounted for the construction phase were evaluated through the LCIA and burdens summed up to those calculated for materials production. Then, a full LCA was performed to compare the eighteen indicators for each alternative construction solution and define the best environmentally friendly alternative for each scenario. Finally, the greenhouse

FIGURE 2. Schematic diagram of the adopted methodology.



gas (GHG) emissions were calculated and the IPCC method (Shine et al. 1990) was used to measure and compare the environmental footprint of each alternative.

5.3 Boundaries of the system

The LCA model is developed according to the standard EN 15804:2012 (CEN/TC350 2012). The system boundaries adopted and the included life cycle modules of the two scenarios are shown in Figure 3 and Figure 4.

Specifically, Figure 3 shows the included modules that were taken into account for the LCA of refurbishment scenario. The analyses were 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 others were considered out of the boundaries.

Contrarily, as shown in Figure 4, 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.

FIGURE 3. System boundaries of the LCA model for the refurbishment scenario.

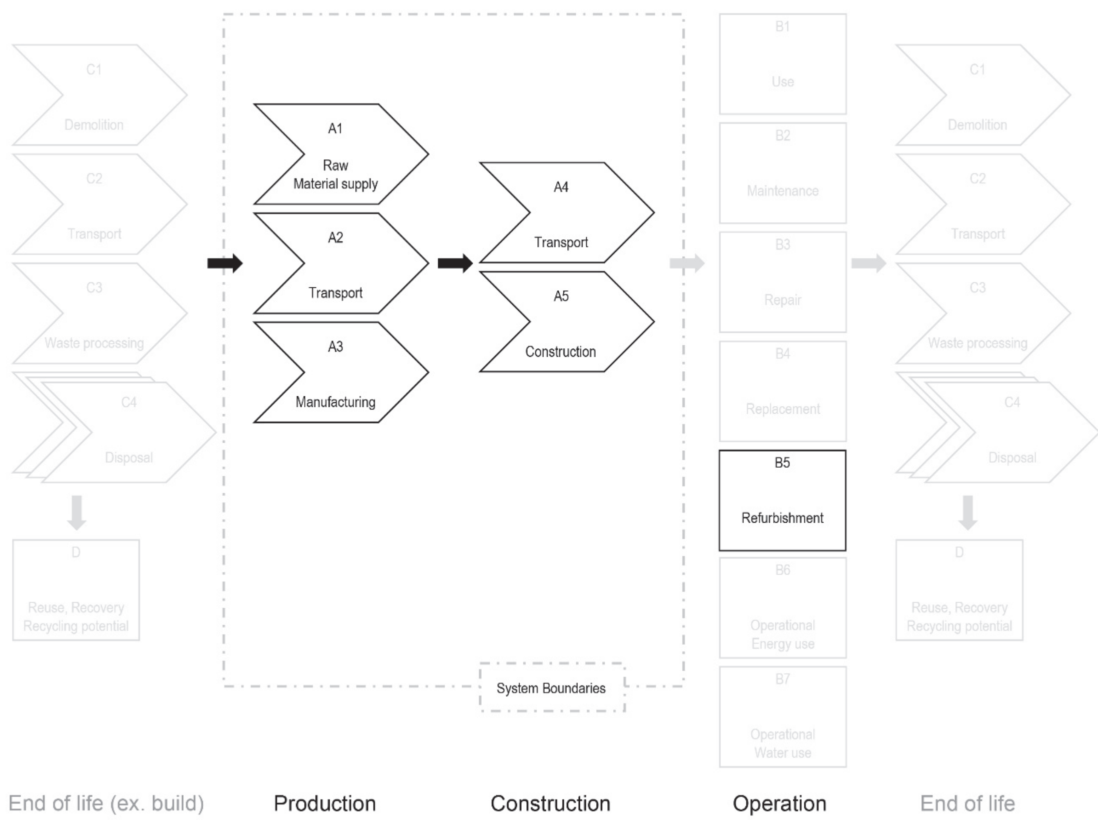
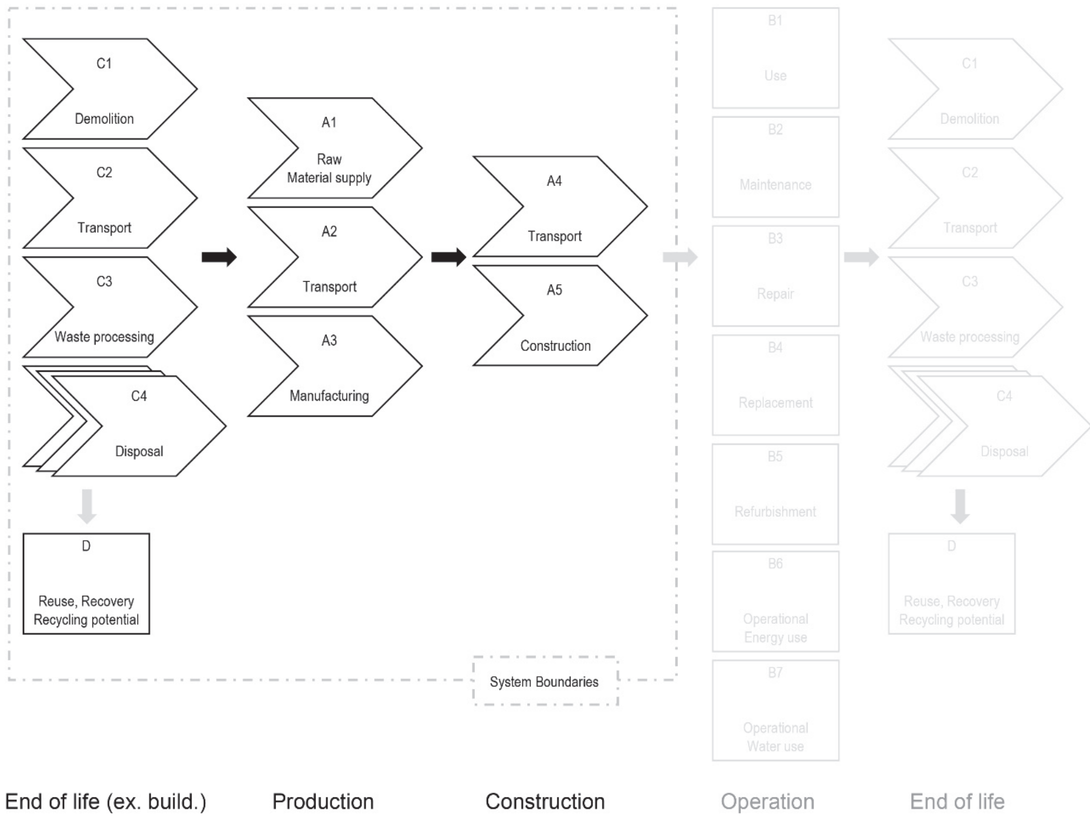


FIGURE 4. System boundaries of the LCA model for the new construction scenario.



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.

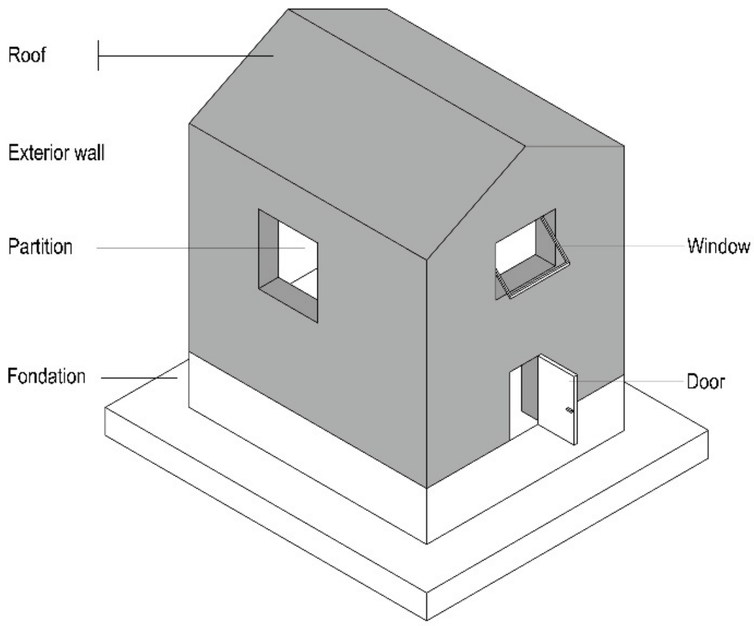
The system boundaries of the products and processes along the LCA are defined according to two criteria. The first considers the second order calculation depth, which includes materials used in processing, transport and other operations. The second criterion considers the cut-off method, which defines 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. As shown in Figure 5, 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, except the roof windows of the existing structure that were assumed to be landfilled in the demolition and reconstruction scenario.

5.4 Product and 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. (Arrigoni et al. 2017).

FIGURE 5. Construction elements of a schematic building. In grey, elements from the envelope that are included in the LCA calculation. In white, all the elements which are excluded from the analysis.



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 the 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/m^2 of CLT was manufactured in WOOD both for walls and for roof. Post-production activities such as drilling cutting and moving required $3.4 \cdot 10^{-3}$ 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 are listed in Table 3 and Table 4. The first shows the vehicles involved for the material transportation and equipment used by construction workers to install the materials needed to refurbish the building. As shown in Table 3, only a small part of the building was 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 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.

The second Table (Table 4) shows that a much larger amount of material from demolition is expected to be wasted and transported to waste treatment centers.

This activity was expected to require almost 6 weeks, with many heavy machines for excavation, material movement and demolition were planned to be used for parallel activities. As for

TABLE 3. Construction activities planned for the installation of materials in refurbishment scenario.

	Duration in days	Number of vehicles	Distance in km	Equipment
Demolition works	7	2	17.0	Electric compact assembly tools and hydraulic crane
Roof	24	2	50.0	Electric compact assembly tools and hydraulic crane
Walls	66	2	50.0	Electric compact assembly tools and hydraulic crane
Finishing	14	1	50.0	Electric compact assembly tools

TABLE 4. Construction activities planned for the installation of materials in new contraction scenario.

	Duration in days	Number of vehicles	Distance in km	Equipment
Demolition works	40	3	17.0	Demolition pliers, semitrailer, hydraulic crane, excavator
Concrete structure	53	3	50.0	Wooden formworks, concrete mixer truck (Euro3), electric pomp for concrete pouring
Roof	111	2	50.0	Electric compact assembly tools and hydraulic crane
Walls	42	2	50.0	Electric compact assembly tools and hydraulic crane
Finishing	14	1	50.0	Electric compact assembly tools

the 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.

5.5 End of life scenarios of demolition waste (mod. C)

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

1. *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;
2. *sanitary landfill:* considered as temporary storage for reactive materials such 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 CH_4 during their decay;

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

In the 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 (Rivela et al. 2006). 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 (Neugebauer and Finkbeiner 2012). 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.

In Table 5, the six different demolished materials are listed and their mass calculated in order to define the impact from transportation and the potential from a disposal scenario. As shown above, almost 97% of the materials are inert, of which 75.6% has no potential for material recovery.

5.6 Loads and benefits beyond the gate (mod. D)

All the loads and benefits from avoided processes and avoided materials that are beyond the boundaries are separately accounted from in module D. In the recycling scenario all the

TABLE 5. Inventory of waste material from building demolition.

Material	Amount	Density	Mass	%	Waste category
	m^3	kg/m^3	t		
Bricks	1,431	1,200	1,717.2	75.6%	Landfill
Concrete	183	2,600	476.7	21.0%	Material recovery
Wood	36	420	15.1	0.7%	Energy recovery
Glass	1	2,600	1.8	0.08%	Landfill
Steel	3	7,960	23.4	1.0%	Material recovery
Tiles	916	40	36.6	1.6%	Landfill

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.

6. RESULTS

6.1 Comparison of alternative structures

The first LCA comparison has been performed at the structural level in order to compare the different alternative structural systems in case of demolition and new construction.

In Table 6 the inventory of the materials needed to fulfil the structural requirements has been listed. Four alternative structural systems were compared, namely: reinforced concrete, CLT, timber frame and steel. The concrete alternative requires the highest amount of material, which is more than three-folds the amount required for the two timber solutions. Following the steel alternative, which in terms of mass, contrary to the others, requires less material for vertical elements due to the optimization of the sections on the base of the larger spans.

Figure 6 shows the overall environmental impact of the four alternative structures.

All the values were normalized on the base of the solution that presented the highest score. The steel solution accounted for the highest impact for all the environmental indicators, except for land use for which no impact was expected due to the nature of the material that is extracted from the quarry as aggregates and limestone for use in concrete.

Except for Global Warming, the two wood alternatives, CLT and timber frame, accounted for relatively high scores from impact on the air, while they registered the lowest scores from damages on water. In terms of scarcity of the resources, both the two wood-based alternatives and concrete one presented roughly the same score for water consumption, while the CLT alternative accounted for a slightly higher score of fossil resource scarcity due to the high glue content to process the material.

6.2 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 as well as from EoL of waste disposal are aggregated and normalized as explained in the previous section. Figure 7 shows the impact scores of each refurbishment alternative.

TABLE 6. Material inventory of the two main building elements according to the four alternative structural systems.

Structure	Roof [kg]	Vertical elements [kg]
Reinforced concrete	60,0714	128,432
CLT	20,452	71,656
Timber frame	15,110	52,938
Steel	57,657	43,827

FIGURE 6. Environmental impacts for four alternative structural systems, calculated according to the ReCiPe method.

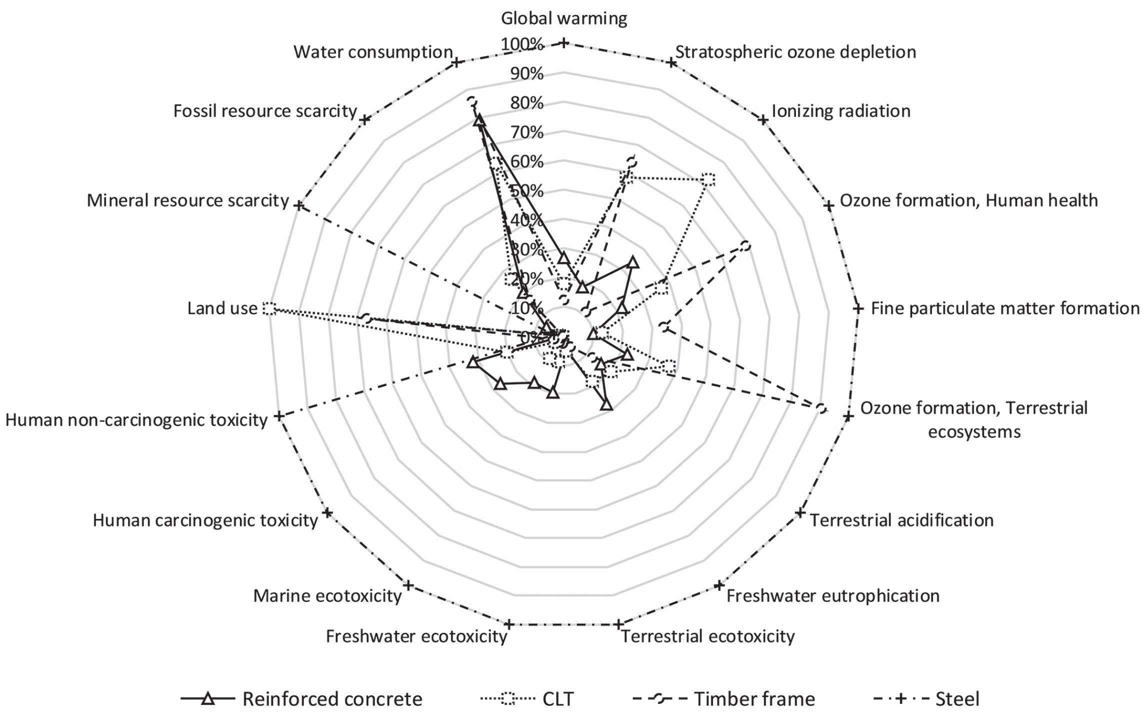
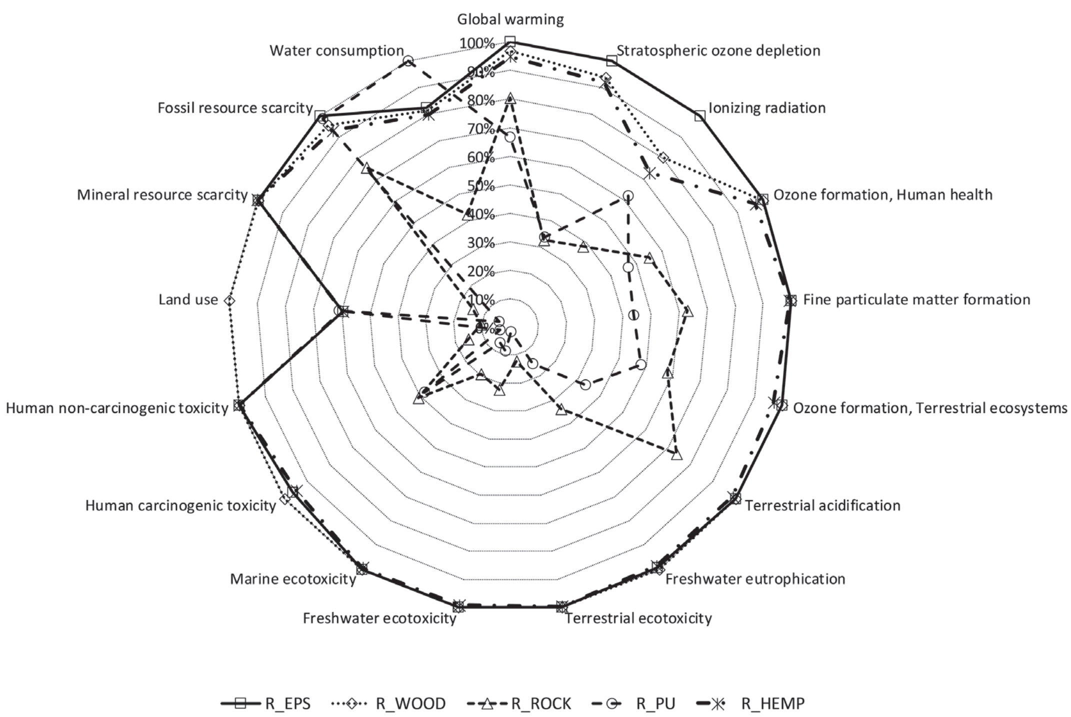


FIGURE 7. Environmental impacts for five alternative construction systems, calculated for the refurbishment scenario according to the ReCiPe method.



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 others and definitely results in a higher impact, particularly on the air pollution.

The two best performing alternatives for the refurbishment scenario were 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 8, where the five different alternative solutions for new construction are compared.

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 wall's assembly. Finally, the two biobased solutions, WOOD and HEMP, accounted for the lowest environmental impacts, and are able to reduce environmental loads by 60–95%, except the land use category due to the nature of the biogenic materials which require space for growing and harvesting.

6.3 Carbon footprint assessment of the construction alternatives

Finally, the ten construction alternatives, five for refurbishment and five for new construction, were compared in order to show the magnitude of impact variation. For this comparison, only

FIGURE 8. Environmental impacts for five alternative construction systems, calculated for the new construction scenario according to the ReCiPe method.

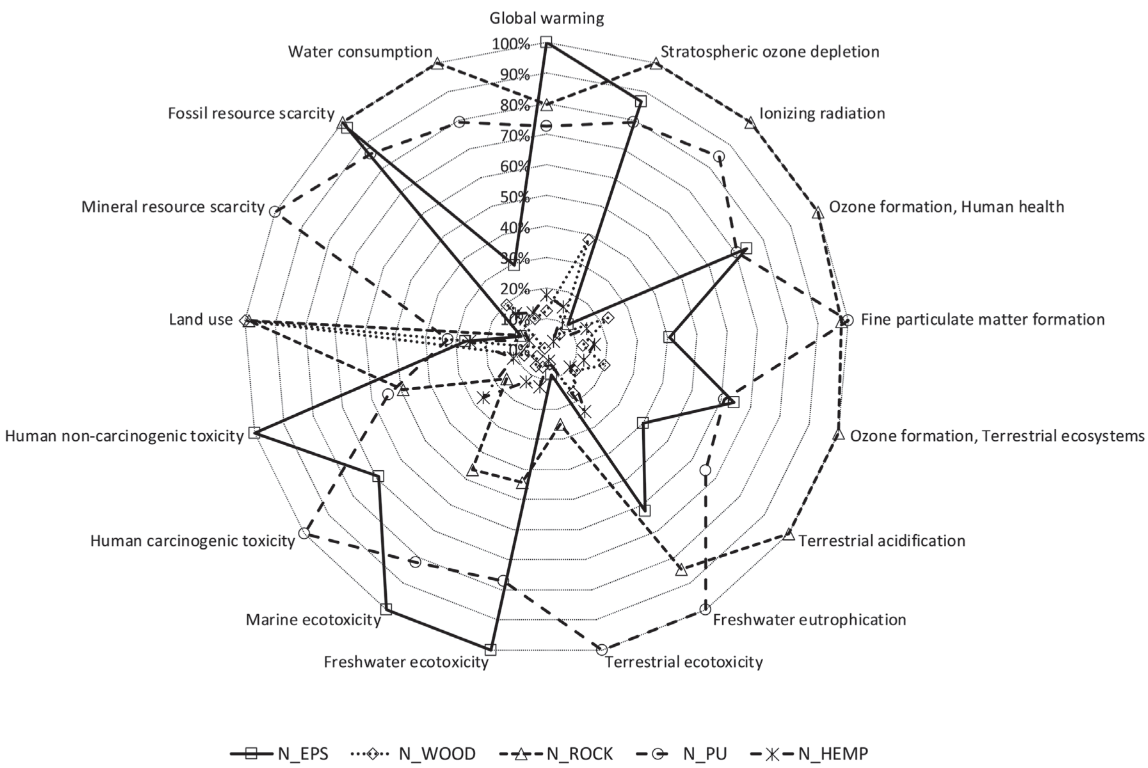
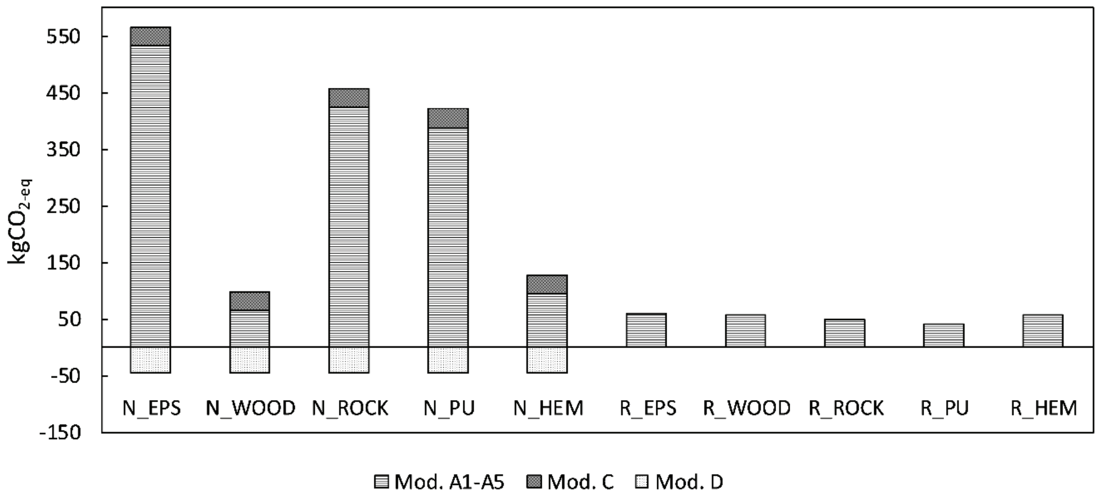


FIGURE 9. Comparison of the Global Warming Potential of the ten alternative construction systems, calculated according to the IPCC 2013 method. According to EN 15804, Mod. A1–A5 states for production & construction, Mod. C for demolition & waste treatment, and Mod. D for benefits & loads beyond the system boundaries.



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 9.

Specifically to Global Warming, the new construction option showed a higher impact compared to refurbishment for each construction alternative. A biobased solution resulted in the most environmentally friendly solution 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 brings the technologies in line with refurbishment options. Only the avoided emissions from virgin materials extraction is taken into account in Module D. The biogenic CO_2 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 emission. Following the two biobased solutions, which are able to save 3–5% of GHG emissions for material production, ROCK, with a 20% saving potential, and finally PU, which was able to save up to 33% of carbon emissions.

7. 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 m^2 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 an existing building considerably affects the global results, contributing to increasing the impact per FU. Synthetic insulation materials, such as EPS and PU, which are applied on a massive system (masonry), account for the highest impacts. Contrary 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 the GWP indicator is considered, even taking into account the benefit from energy and material recovery from demolition waste (module D), refurbishment can always be considered the best environmentally friendly alternative. Additional benefit from temporary carbon storage can be expected if biogenic CO_2 would be included in the calculation (Pittau et at. 2019). 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 the effect of repair and replacement of exhausted components during their service life and end of life.

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