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The role of LCA in the renovation's early decision-making for the design of a multifunctional, modular building envelope system

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Abstract: The renovation of buildings has a high capacity to influence the environmental impacts and global objectives of climate change mitigation. In the context of designing low-energy buildings with minimized environmental impacts, the life cycle assessment (LCA) has been proven a straightforward method, to evaluate the direct and indirect environmental impacts of a building concept. Even though it is the most energy-intensive element, the use phase is not only a source of environmental concern but also the whole life cycle of the building and its components. However, energy-efficient renovation decisions tend to be financially motivated events, subject to exogenous constraints or barriers, that do not integrate whole life cycle thinking. This study aims to identify how the LCA information can be considered in comparing renovation options. compare renovation options, taking into account the modular envelope system developed as part of the European research project ENSNARE (ENvelope meSh aNd digitAl framework for building Renovation) case study. The study analysed different renovation scenarios, generated according to combinations of renewable energy sources and compare them to the base case and typical renovation scenario. Such information can support the design team in making decisions that consider the whole building and its components' life cycles.

1. Introduction

To reach the potential of the existing building stock to be renovated up to an energy-neutral standard, it is crucial to improve the way we carry out building renovation, [1] increasing both the rate and depth of the renovation [2, 3]. Furthermore, the renovation of buildings has a high capacity to influence the environmental impacts and global objectives of climate change mitigation. At present, buildings are responsible for 39% of global energy-related carbon emissions. Out of this, 28% of emissions come from operational emissions, which is the energy consumed to operate and maintain buildings for heating, cooling, and powering, while the remaining 11% arise from materials and construction. Thus, reducing carbon emissions in this sector is an effective and economical means to alleviate the severe consequences of climate change. [4] In the context of designing low-energy buildings with minimized environmental impacts, the Life Cycle Assessment (LCA) has been proven a straightforward method, to evaluate the direct and indirect environmental impacts of a building concept. [5] [6] The upcoming EPBD recast also brings the role of LCA further into the focus of renovation design decisions. It specifies that “The whole life-cycle performance of buildings should be taken into account not only in new construction but also in renovations through the inclusion of policies and reduction targets of whole life-cycle greenhouse gas emissions in Member States’ building renovation plans”. [7] However, energy-efficient renovation decisions tend to be financially-motivated events, subject to exogenous constraints or barriers [8] that do not integrate whole life cycle thinking.

To address that issue, life-cycle analysis methodologies should be integrated into the renovation design process, providing the design team with a valuable set of information and data which enable understanding, improving and optimising the sustainability performance of a building, beyond energy efficiency. Concepts related to environmental performance and resource efficiency should be consolidated in the early stages of a project, in its design phase. [9] This study aims to identify how the LCA information can be considered in comparing renovation options. The study assesses renovation scenarios, as they were generated according to the different combination of renewable energy sources and compare them to the base case and typical renovation scenario. A life-cycle analysis (LCA) and life-cycle costing (LCC) is performed for each of those scenarios, to identify which decisions influence the performance and how it can be optimized. The renovation system considered in the analysis is the modular envelope system developed as part of the European research project ENSNARE (ENvelope meSh aNd digitAl framework for building Renovation). Finally, the study provides conclusions from the LCA that can influence renovation-specific design decisions regarding the technologies' configuration in the module to be installed on an existing building.

2. Method

Given the objective of the paper to support early design decisions regarding renovation, the study aims at comparing renovation scenarios, particularly regarding the integration of active technologies. It is considered a preliminary study, with the objective to direct the design decisions. The first step is to collect data on the existing building and define scenarios. The study uses a pilot case to evaluate the design decisions related to the modular renovation system. The evaluation is based on an LCA and LCC that considers both the operational and embodied energy. Based on this assessment of different scenarios, we identified the technical options that have better potential and which parameters can determine the decisions in the early stages.

2.1. LCA and LCC method

For this study, the LCA and LCC are performed in the early stages of the renovation process to accelerate the decision-making process. The OneClick LCA tools for Life-cycle Assessment and Life-cycle Costing [10] were used for the evaluation of each renovation scenario with a life-cycle perspective spanning the service life of the renovated building, based on the standards ISO 14040 [11] and following EN15978 [12]. The environmental assessment was based on embodied and operational GHG emissions, while the economic assessment was based on investment and operational costs, considering a life-span of 60 years. The operational energy was estimated using dynamic building simulation. The simulation of the different scenarios is performed using DesignBuilder (v. 6.1.0.006) modelling software based on the open-source Energy Plus simulation engine. The operational costs (both financial and environmental) were derived from the energy use estimated by a prior energy simulation, using unitary costs (EUR/kWh) and GHG emission factors (kgCO2eq/kWh). Embodied carbon is calculated from the databases of each renovation technology, considering the sizing (m2, kWh...) adopted for each scenario. Figure 1 presents the schematic diagram of the workflow to execute the LCA for each renovation scenario. Regarding environmental impact, the outputs presented in Table 3 allow us to compare the different scenarios generated. The required inputs are extracted from environmental product declarations (EPDs) of default databases (Table 1).

Table 1. Overview of the EPDs of products used in the renovation scenarios

Material/Component	**EPD/datapoint name**	**Database**
EPS Insulation	EPS 80 insulation	EPD International [13]
Double glazed window	Window with insolated double-glazing	IBU [14]
Rendering mortar	Putzmörtel Armierungsputz	IBU [14]
Paint	Dulux Trade Weathershield Smooth Masonry	MRPI [15]
Mineral wool	ISOVER UNI-skiva 35	EPD Norge [16]
Trespa panel	High pressure laminate (HPL) panels, Meteon®	IBU [14]
Steel frame	Structural steel profiles, generic, 60% recycled content	One Click LCA [17]
Solar thermal collector	Capteur solaire thermique	INIES [18]
PV Panel	Solar panel photovoltaic system	One Click LCA [17]
Electricity	Electricity, Estonia	One Click LCA [17]
Natural gas	Natural gas	One Click LCA [17]

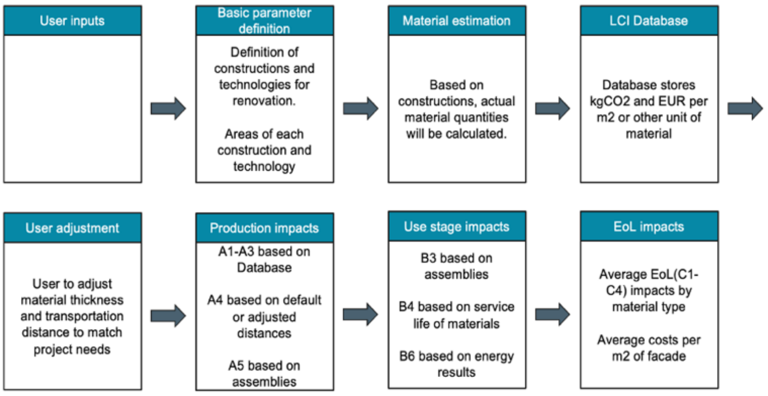

Figure 1. Schematic LCA workflow

2.2. *Description of the ENSNARE system.*

The multi-functional envelope consists of a modular frame that facilitates the mechanical assembly and functional interconnection of all components and networks, integrating technologies such as thermal insulation, active windows, and solar thermal and photovoltaic panels.

2.2.1. Industrialized mesh. The modular industrialized mesh acts as an additional outer skin and aims at improving the performance of the existing façade. To achieve the maximum degree of industrialization, thermal insulation must be incorporated into all modules of the façade, which requires careful study of the requirements related to air and vapour permeability, water tightness and the thermal resistance of the whole [19]. The components of the system are the following:

- Structural elements: Horizontal and vertical aluminium profiles provide self-support and seal the perimeter of the module, anchored to the structure of the building by fixing brackets.
- Infill elements: The infill elements or panels can be transparent, in which case glass is used mainly, and opaque, which can be executed with different types of panels. In this pilot case, the Trespa Meteon phenolic panel is considered as the finishing material of the opaque panels.

2.2.2. Active components. To eliminate the energy demand of the building, towards zero-energy renovation, the generation of energy onsite is required. To apply the system to the pilot case, the panels' dimensions and the modulation are designed, according to the building's geometry and orientation. The south façade of the pilot case was selected as a reference to compare the different scenarios.

To this end, the system allows the integration of active technologies, more specifically Solar thermal collector (ST), Photovoltaic-thermal hybrid panel (PVT), and Photovoltaic panel (PV). **Table 2** provides an overview of the active components and their efficiency specifications that were taken into account for the energy calculations.

Table 2. Active components considered for the renovation scenarios

	Solar thermal collector (ST)	Photovoltaic-thermal hybrid panel (PVT)	Photovoltaic panel (PV)
Efficiency	η_thermal = 0.5533	η_thermal = 0.3344, η_electric = 0.150	η_electric = 0.150

3. Results

3.1. *Scenarios Definition*

Defining the scenarios constitutes an important step in the method, as it determined which parameters can be compared. The scenarios we developed how the modular system performs over the life cycle compared to do-nothing to the existing building, as well as compared to a typical external insulation renovation. This is why we have introduced an option of the modular system without the active components. Furthermore, we compare scenarios with different active systems, in a realistic configuration, as discussed in 2.4. This has resulted in different zones of the façade, that allow the integration of technologies, as shown in Figure 2.

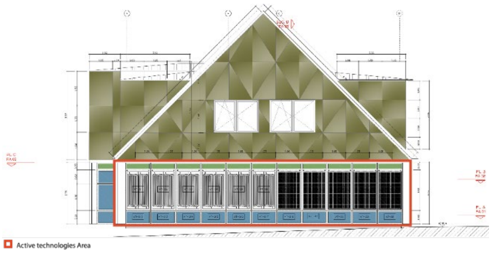

Figure 2. Design of the South façade of the pilot case – Scenario 6: Combination of the different technologies. The bright green section within the active technologies area indicates the registration area which is needed in all active technologies for managing the systems' installation and maintenance [20]. The motivation for this combination relates to the project objective to showcase different technologies.

Table 3 presents the scenarios that were investigated. Based on the configuration and the façade geometry, the area of each technology was determined.

Table 3. Overview of the façade characteristics per scenarios

	0. Existing Building	1. Typical renov.	2. All Trespa	3. Trespa+ All ST	4. Trespa+ All PVT	5. Trespa+ all PV	6. Combi-nation
Scenarios Description	Plaster, wood walls, wood structure,wood walls, plaster.	ETIS with 12cm EPS and PVC-frame, double-glazing window	Aluminium frame, 15 cm mineral wool insulation, opaque panel wood-composite panel Trespa	Same as 2, on the triangular part of the façade. Solar panels (ST) in the active technology area	Same as 2, on the triangular part of the façade. Photovoltaic-thermal hybrid panel (PVT)	Same as 2, on the triangular part of the façade. Photovoltaic panel (PV)	Same as 2, on the triangular part of the façade. Photovoltaic-thermal hybrid panel (PVT)
Insulation* area (m2)	N/A	76	76	76	76	76	76
Double glazed windows (m2)	6	6	6	6	6	6	6
Trespa panel** area (m2)	0	0	76	38	38	38	38
Façade av.U-value (W/m2K)	0,545	0,200	0,189	0,152	0,140	0,189	0,160
Registration area **	0	0	0	5	5	5	5
ST area (m2)	0	0	0	36	0	0	15,2
PVT area (m2)	0	0	0	0	36	0	12,7
PV area (m2)	0	0	0	0	0	36	8

*Insulation material: Mineral wool 100mm; ** Trespa panel thickness: 8mm

3.2. *Operational energy*

The annual energy consumption of the different scenarios was calculated through dynamic simulation of the whole building's thermal behaviour and the resulting energy consumption. It was calculated based on the building features, HVAC schedules, occupancy patterns, internal gains, and system loads. Case 0 is modelled using the existing conditions of the real building and validated with the available energy bills. The rest of the cases are simulated with the same features only changing the thermal characteristics of the analyzed façade. Figure 3 presents the total energy use in kWh and Figure 4 breaks down the annual energy consumption in electricity, natural gas for heating and natural gas for domestic hot water (DHW). It also presents the energy generation of electricity and DHW, as applicable to the respective scenarios. Based on these results, the following observations can be made:

- Heating is the main source of energy consumption. The difference between the scenarios is not significant, because the renovation is applied only on one of the building's facades.
- In all scenarios with DHW generation, the production surpasses the consumption. Particularly in the "All ST" scenario, the production is more than triple the demand.
- The electricity generation in all scenarios that PV apply does not reach the electricity consumption.
- The existing building has the highest demand, while scenarios 1 and 2 have similar performance.
- Of the all energy generating scenarios, the one with only PV is the worst performing in terms of total energy use (in kWh)

- The best-performing scenario is 3, with the active technologies area to be covered with solar thermal collectors. This can be attributed to the high output of the DHW.

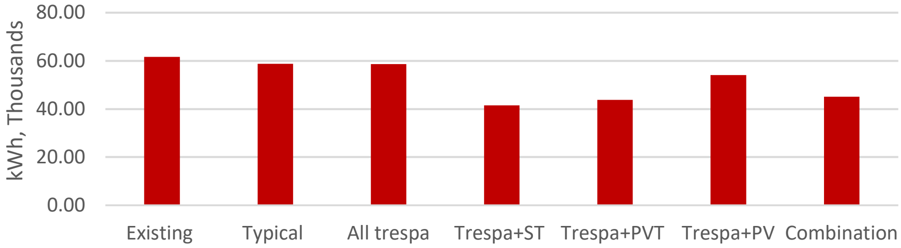

Figure 3. Total energy use of the whole building in kWh/yr per scenario, including consumption and generation.

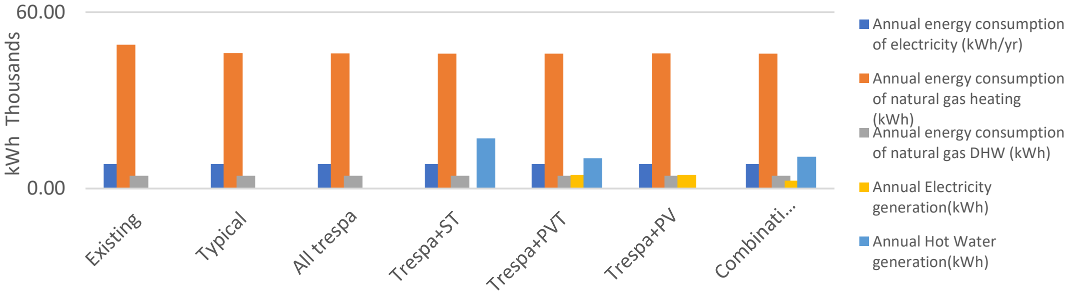

Figure 4. Overview of the different scenarios' annual energy consumption and generation, as applicable.

3.3. *Life cycle analysis LCA and Life Cycle Costing*

As shown in Figure 5, the lowest Global Warming Potential (GWP) impact is achieved in the ENSNARE renovation scenario with PVT panels. This is because of the increased energy production achieved compared to the other options. The impacts of façade are considered negligible compared to the savings in operational energy that they offer. With the assumed, typical façade setup, the operational energy is the main driver of the GWP impacts. As shown in Figure 6 the main difference in life cycle cost is between options with and without active technologies. Similarly, with carbon emissions, the costs are driven mostly by the energy cost and in this case also by the cost of the active technologies. It is worth noting that the solar thermal option results in a similar cost to options with no active technologies. This is due to the assumptions made for the cost per kWh of natural gas and electricity.

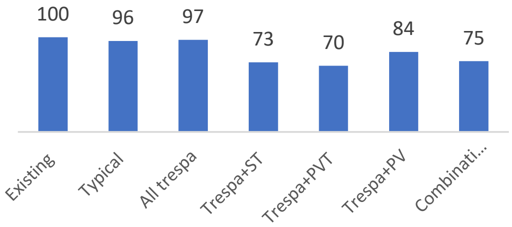

Figure 5. Global Warming Potential (GWP), expressed in % of the existing. The lower the percentage, the lower the GWP of the scenario

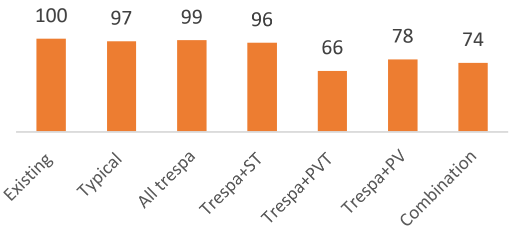

Figure 6. Life-cycle cost, discounted with inflation, expressed in % of the existing

4. Discussion and Conclusion

The study analysed different scenarios for applying passive and active technologies to upgrade existing buildings. As the case study in the paper, we have compared the modular ENSNARE solutions not only against the existing baseline but also against a 'typical' ETICS renovation system. Based on the LCA and LCC, taking into account the operational energy as well, the following key conclusions can be drawn.

- The application of active systems with energy generation has a considerable advantage compared to options with no energy generation
- Between the active technologies compared, solar thermal has the better energy performance, however, it is the PVT that performs better in terms of LCA and LCC. This can be explained by the GHG and cost factors for the different fuels, as well as the systems' efficiencies.
- The option with only PV performs the lowest among the active technologies, highlighting the potential to integrate solar thermal as well
- Comparing the modular system with a typical renovation we see that both energy and LCA are similar, which gives an advantage to the modular system that can further integrate active technologies.
- The scenario that combined different technologies performs well, which shows that the combination of technologies is also possible if required by the design objectives of a project.

These conclusions can inform the design decisions of the renovation. A limitation of the study is that it was applied to a specific building and it might be different when applied to another typology. Nevertheless, we aimed at a realistic design process, which needs to adjust to the building's characteristics. The comparison of scenarios for different building typologies will be part of further research. Furthermore, the LCA did not consider the uncertainty of future climate and changes in the use of the building, as those parameters are outside the scope of the paper.

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