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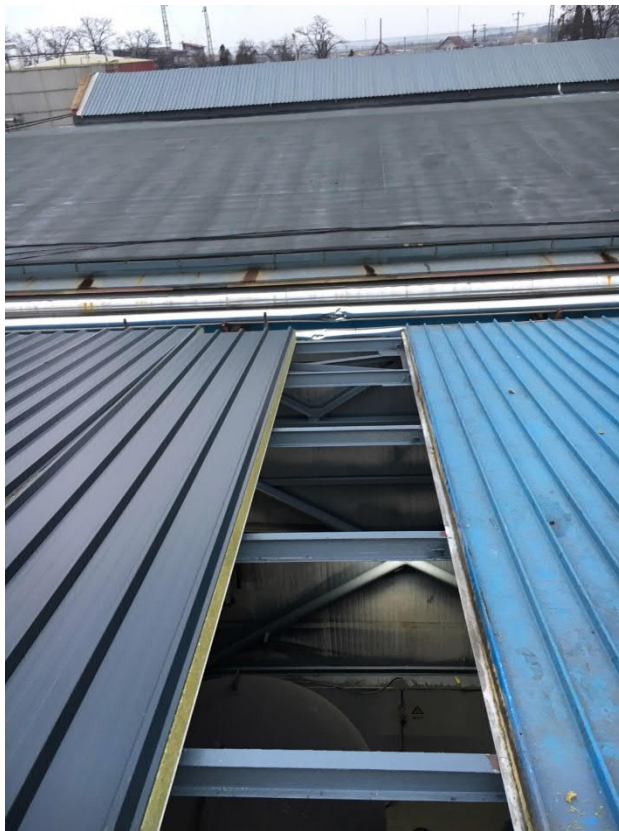
PROVISIONS FOR GREATER REUSE OF STEEL STRUCTURES

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Evaluation of hybrid systems performance

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Executive summary

This report presents a theoretical study on new hybrid solutions for claddings regarding their contribution to the improvement of the overall performance of buildings design from reclaimed elements in the scope of RFCS project PROGRESS “Provisions for greater reuse of steel structures”.

The following aspects will be assessed:

- Energy efficiency;
- Environmental benefits according to the recommendations developed in Task 5.1;
- Life Cycle Costs according to the recommendations developed in Task 5.2;
- Fire safety;
- Sound insulation.

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1. Introduction

For many buildings, it is the failure or deterioration of the envelope that trigger its premature end of life. This can be aesthetic deterioration, changing architectural design or, as is often the case, the need to update the envelope to modern standards of thermal performance (the European Energy Performance of Buildings Directive demands a 20% energy savings target by 2020 [1]). The envelope has a major influence on both the interior comfort and the energy consumption of a building, aspects on which we place continuously and high growing demands leading into having high demands on the performance of the building envelope as well [2].

As the environmental and the economic impact in construction sector are highly important aspects in the last decades, the building envelope needs innovative hybrid elements, which allow an easy adaption to new requirements, a simple dismantling and as possible, to ensure a future possible reuse of the components and recycling of the materials. Hence, components and materials for the building envelope are to be chosen and connected in such a manner that they can be reused or recycled after a building's end-of-life [3]. Moreover, retrofitting solutions should be able to integrate the loops of circular economy (such as refurbishment, re-use and recycling) [4] [5].

Retrofitting can support a new economic life and adjourns the end-of-life of a building, having the effect of increasing the present value of the building and reducing operational costs, as such the net annual return remains positive for a longer period. Considering environmental impact of the energy and waste disposal costs of demolishing and reconstruct of a building in comparison with re-use of a building, provides strong incentives for a transition to more sustainable energy use, less wasteful use of new construction materials and a greater use of existing building stock [5].

This study aims at the contribution to the improvement of the overall performance of buildings envelope using hybrid solutions for claddings. Retrofitting the building's envelope ensures comfort without prejudice functional needs. One of the important parts used in the retrofitting process of a building envelope regards walls' and roof's insulation. The results of the present study show the environmental and economic impact in terms of greenhouse gas (GHG) emissions and costs of several envelope rehabilitation solutions which provide the same energy performance. Further, aspects related to fire safety and sound insulation are presented.

2. Aim of the study

2.1 Common envelope systems used in single-storey steel-framed buildings

This paragraph describes the most common existing systems for envelopes of single-storey steel-framed buildings, both for walls and roofs. The solutions presented below will be rehabilitated in Section 2.2 to fulfil the modern standards of thermal performance and analysed in detail in Chapters 3 to 5.

2.1.1 Envelope Systems for Walls

2.1.1.1 Built-up wall system

The built-up wall system is consisting of an external and an internal trapezoidal steel sheet, both fastened to the side rails, having insulation in-between the side rails. An additional layer of vapor barrier foil stands enclosed by the internal steel sheet and the thermal insulation. In this study case a 0.5 mm thick steel sheet (S250 GD+Z) was considered for both internal and external steel sheets, while the thermal insulation was a 100 mm thick mineral wool (density: 20 kg/m³).

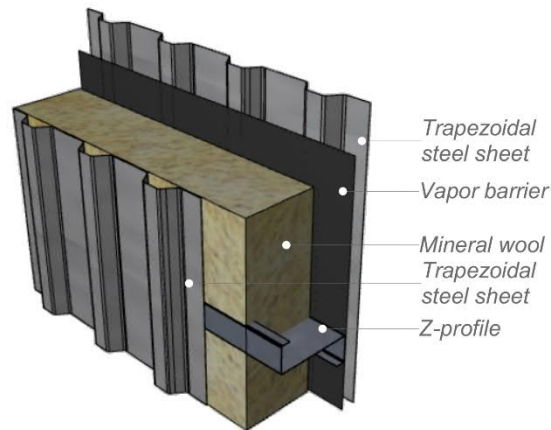


Figure 1. Built-up wall system

2.1.1.2 Sandwich panels wall system

The envelope system resides in sandwich panels (an insulating foam-core with two steel sheets skins) attached vertical to the thin-walled steel side rails (Z-steel profiles) or horizontally to the main structure. The sandwich panel weighted in the study case was a PUR (polyurethane insulation) based sandwich panel (density: 30 kg/m³), with a 60 mm thick insulation core and 0.5 mm steel sheets skin (S280 GD).

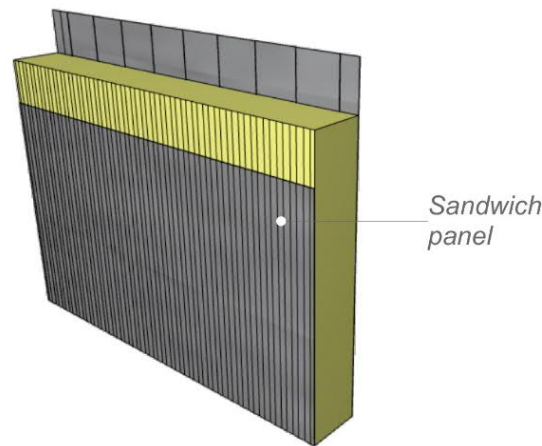


Figure 2. Sandwich panels wall system

2.1.1.3 Liner tray wall system

A built-up wall system consisting in an external trapezoidal steel sheet installed over an encased insulation core which is attached to the load bearing structure. Additional layer of vapour barrier foil stands between the load bearing structure and the thermal insulation. For the case study it was took into consideration a 0.5 mm thick trapezoidal steel sheet with a 20 mm high rib (S250 GD+Z) and a 100 mm thick mineral wool insulation (density: 100 kg/m³) encased in a 0.75 mm thick liner tray (S320GD+Z).

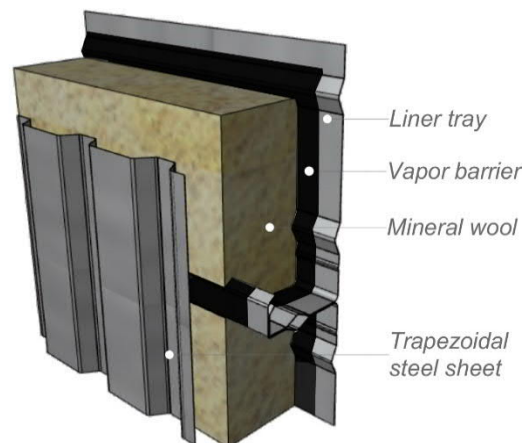


Figure 3. Liner tray wall system

2.1.2 Envelope Systems for Roofs

2.1.2.1 Built-up roof system I

A built-up roof system consisting of an external and an internal steel sheet both fastened to the Z-purlins, having insulation in-between the purlins. Additional layer of vapour barrier foil stands enclosed by the internal steel sheet and the thermal insulation. In this study case a 0.4 mm thick trapezoidal steel sheet with a 20 mm high rib (S250 GD+Z) was considered for the internal steel sheet, a 0.5 mm thick trapezoidal steel sheet with a 45 mm high rib (S250 GD+Z) for the external

steel sheet, while the thermal insulation was a 100 mm thick mineral wool (density: 20 kg/m³). The purlins counted in the study were 150/2.5 mm Z-steel profile (S350 GD+Z).

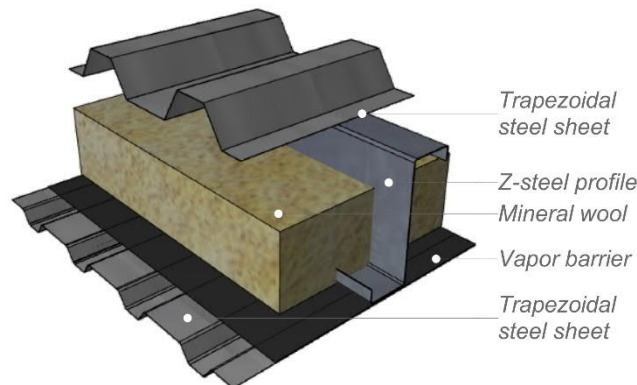


Figure 4. Built-up roof system I

2.1.2.2 Sandwich panel roof system

The envelope roof system resides in sandwich panels (an insulating foam-core with two steel sheets skins) attached to the thin-walled steel purlins. The sandwich panel considered in the case study was an 80 mm PUR insulation based sandwich panel (density: 30 kg/m³), with a 0.5 mm thick steel sheet (S280 GD) for the internal steel sheet and a 0.6 mm thick steel sheet (S280 GD) for the external steel sheet, while the purlins were 150/2.5 mm Z-steel profile (S350 GD+Z).

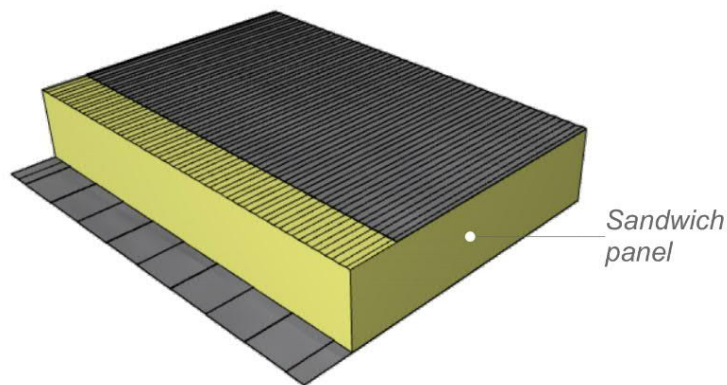


Figure 5. Sandwich panel roof system

2.1.2.3 Built-up roof system II

A built-up roof system consisting of two-layer thermal insulation installed over a liner tray fastened to the thin-walled steel purlins. Additional layer of vapour barrier foil stands between the liner tray and first layer of insulation. As an outer skin stands a trapezoidal steel sheet. For the case study it was took into consideration a 0.75 mm thick liner tray with a 70 mm height (S320 GD) and a first layer of 70 mm thick rockwool insulation (density: 100 kg/m³). A 50 mm high steel spacers stand between the two layers of thermal insulation. The second layer of insulation consists of 50 mm thick rockwool (density: 100 kg/m³), while the external steel sheet considered was a 0.5 mm thick trapezoidal steel sheet with a 20 mm high rib (S250 GD+Z). The purlins counted in the study were 150/2.5 mm Z-steel profile (S350 GD+Z).

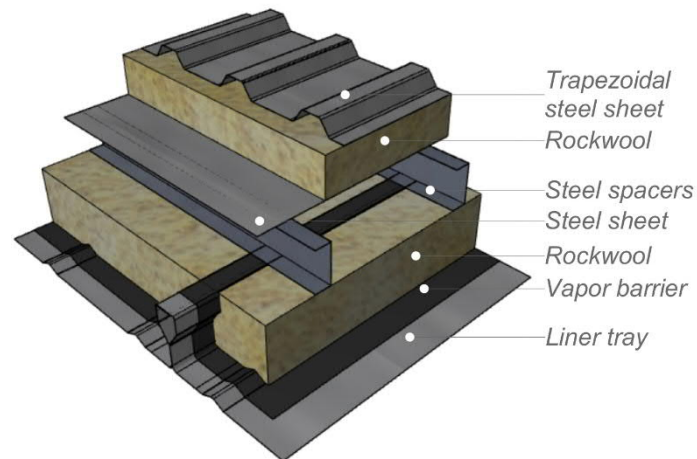


Figure 6. Built-up roof system II

2.1.2.4 Deep corrugated trapezoidal roof system

The roof system consists of trapezoidal steel sheeting, vapour barrier, insulation layer and hydro insulation membrane. The deep corrugated trapezoidal roof system is connected to the main frame with screws or shooting nails. In this study case a 0.8 mm thick high-rib steel sheet (with a rib height of 135 mm) was considered, on top of which stands 120 mm thick rockwool (density: 100 kg/m³). The outer skin consists of two-layer single ply membrane (3 mm).

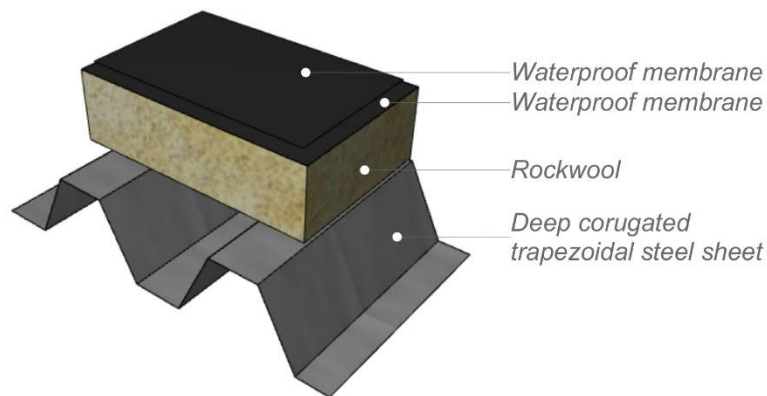


Figure 7. Deep corrugated trapezoidal roof system

2.2 Rehabilitation solutions for the envelope systems used in single-storey steel-framed buildings

This paragraph presents the rehabilitation solutions of the existing systems for envelopes presented in Section 2.1, both for walls and roofs. The solutions presented below will be analysed in detail in Chapters 3 to 5.

2.2.1 Rehabilitation options for Wall Envelope Systems

2.2.1.1 Case 1: Built-up wall system

Option a) The external steel sheet is removed from the existing envelope system and a new 80 mm thick sandwich panel is installed over the remaining original built-up wall system. The sandwich panel is a PUR insulation-based sandwich panel (80mm, density: 30 kg/m³), with a 0.4 mm thick steel sheet (S280 GD+Z) skins.

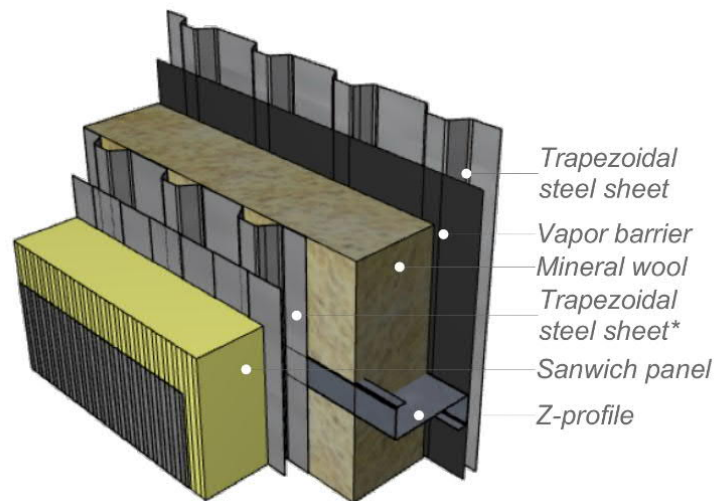


Figure 8. Case 1a – Rehabilitated built-up wall system

Option b) Over the existing envelope system is attached a sandwich panel. The existing trapezoidal steel sheet (*) is not removed. The sandwich panel has the same characteristics as in case 1.a.

2.2.1.2 Case 2: Sandwich panels wall system

Over the existing envelope system are installed 50 mm height Ω (35/2.5 mm) steel rails (S235) and an 80 mm PUR sandwich panel (density: 30 kg/m³), with a 0.5 mm thick steel sheet (S280 GD+Z) skins.

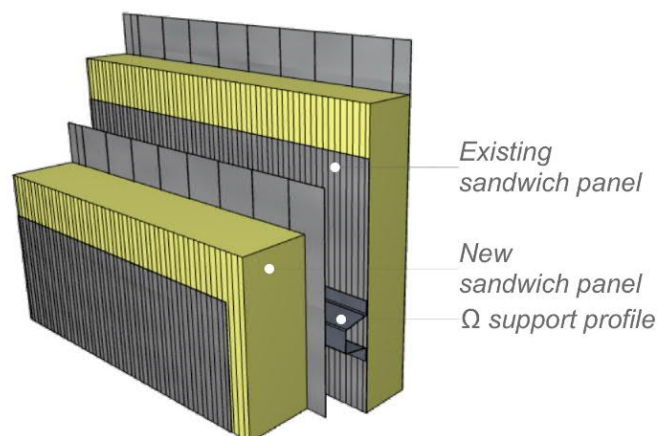


Figure 9. Case 2 – Rehabilitated sandwich panels wall system

2.2.1.3 Case 3: Liner tray wall system

The outer trapezoidal steel sheet is removed from the existing wall envelope system and a sandwich panel is installed over the remaining original built-up wall system. The sandwich panel is an 80 mm PUR insulation-based sandwich panel (density: 30 kg/m³), with a 0.5 mm thick steel sheet (S280 GD+Z) skins.

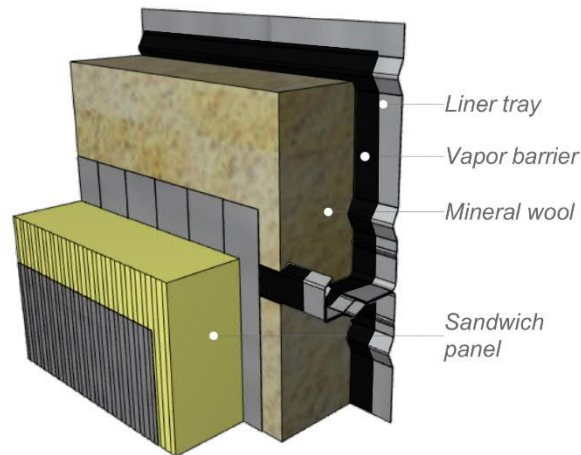


Figure 10. Case 3 – Rehabilitated liner tray wall system

2.2.2 Rehabilitation options for Roof Envelope Systems

2.2.2.1 Case 4: Built-up Roof System I

Option a) The external steel sheet is removed from the existing envelope system and a sandwich panel is installed over the remaining original built-up roof system. The sandwich panel is a PUR insulation-based sandwich panel (80mm, density: 30 kg/m³), with a 0.4 mm thick steel sheet (S280 GD) skins.

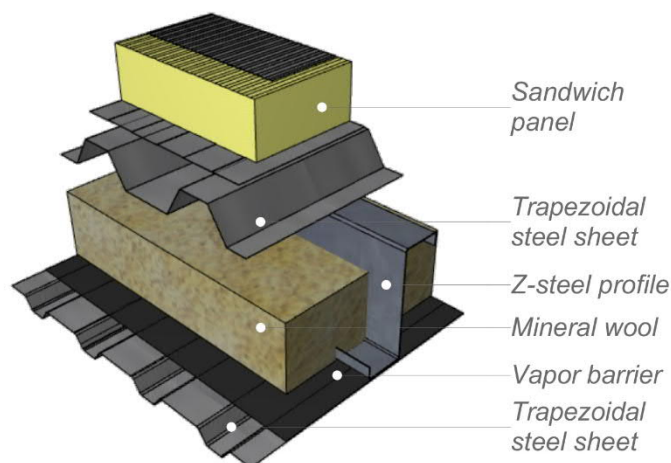


Figure 11. Case 4 – Rehabilitated built-up roof system I

Option b) Over the existing envelope system is attached a sandwich panel. The sandwich panel has the same characteristics as in case 4.a.

2.2.2.2 Case 5: Sandwich panels-based roof system

Over the existing envelope system are installed 50 mm height Ω (35/2.5 mm) metal rails (S235) and an 80 mm PUR sandwich panel (density: 30 kg/m³), with a 0.5 mm thick steel sheet (S280 GD) skins.

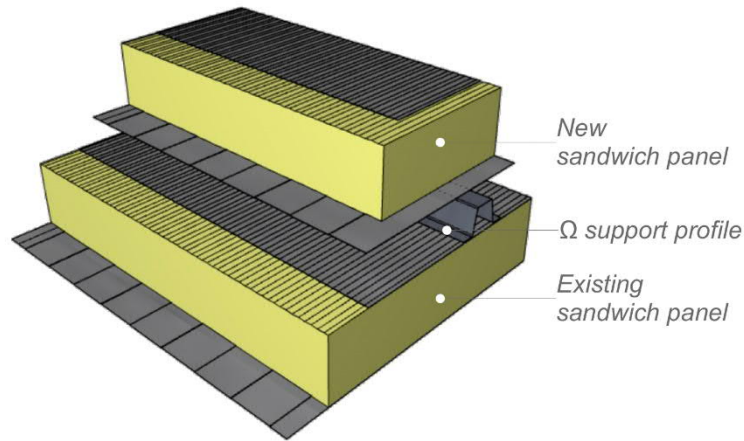


Figure 12. Case 5 – Rehabilitated sandwich panels-based roof system

2.2.2.3 Case 6: Built-up Roof System II

The external steel sheet is removed from the existing roof system and another layer of 100 mm thick rockwool is installed to the remaining original built-up roof system. On top of the rockwool insulation are attached two layers of hydro insulation membrane (1.5 mm thick single-ply membrane).

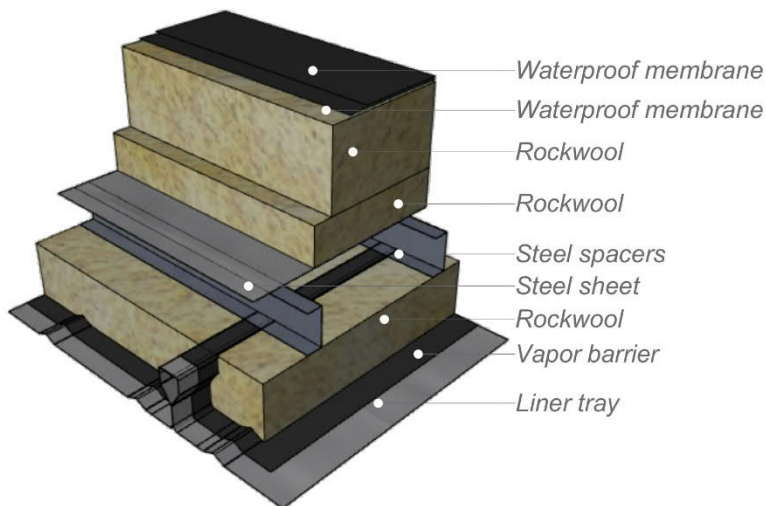


Figure 13. Case 6 – Rehabilitated built-up roof system II

2.2.2.4 Case 7: Deep Corrugated Trapezoidal Roof System

The external layers of hydro insulating membrane are removed from the existing roof system and another layer of 100 mm thick rockwool is installed to the remaining original built-up roof system. On top of the rockwool insulation are attached two layers of hydro insulation membrane (1.5 mm thick single-ply membrane).

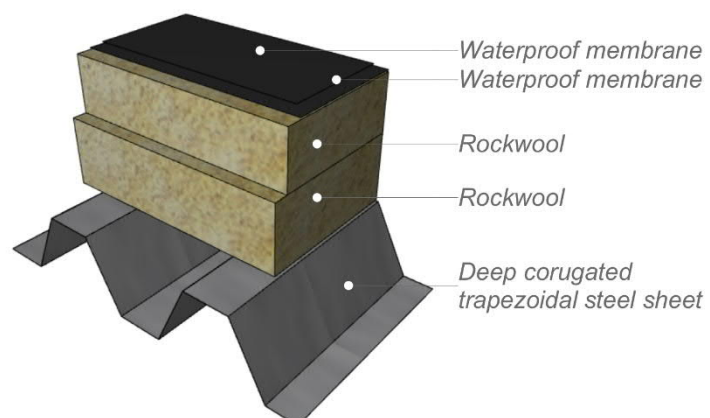


Figure 14. Case 7 – Rehabilitated deep corrugated trapezoidal roof system

3. Energy efficiency assessment

Over the last few years, energy performance has become a very important aspect in the equation of buildings being directly related to its operational. For example, an energy efficient home has lower monthly bills and maintenance costs and if we consider a period of 50 years, we can reach a value of 2-3 times higher than the initial cost of the building.

In terms of thermal performance, the heat transfer coefficient U measures the amount of energy that is transferred through the wall, measured in $W/m^2 \cdot K$ and is the inverse of thermal resistance, $R = 1/U \text{ m}^2 \cdot K/W$. They are complementary values that measure the same thing - the heat transfer through a surface. The difference is in the nomenclature. In Romania, for example, the R value is used, as opposed to Germany where they use the U value.

The envelope systems have been compared using the dedicated online Ubakus software [7]. The external and internal temperatures were considered at the values of $-5^\circ C$ and $20^\circ C$ respectively. Also, a similar heat transfer coefficient for all systems after the rehabilitation process was targeted.

3.1 Assessment of the wall envelope systems

3.1.1 Case 1: Built-up wall system

For the built-up wall system, the overall heat transfer coefficient for the initial set-up reached a value of $U=0.303 \text{ W/m}^2 \cdot K$. After the rehabilitation process, this value reached $U=0.155 \text{ W/m}^2 \cdot K$. The difference between the two upgrades is the removal/keeping the external steel sheet of the initial envelope systems.

Table 1: Thermal resistances of layers in built-up wall system

[mm]	Material	λ [W/mK]	R [$m^2 K/W$]
Initial wall system			
	Thermal contact resistance*		0.13
0.5	Internal steel sheet	50	0
0.25	Vapor barrier	0.17	0.001
100	Mineral wool	0.032	3.125
0.5	External steel sheet**	50	0
	Thermal contact resistance*		0,04
101,25	Whole component		3.296
Wall system after rehabilitation (additional layers)			
0.4	SW panel (PUR) steel sheet	50	0
79.2	SW panel (PUR) insulation	0.025	3.168
0.4	SW panel (PUR) steel sheet	50	0
	Thermal contact resistance*		0,04
18,125	Whole component		6.465

* Thermal contact resistances according to DIN EN ISO 6946 [9] for the U -value calculation. $R_{si}=0.25$ and $R_{se}=0.04$ according to DIN 4108-3 [10] were used for moisture proofing and temperature profile.

** Removed layer according to the rehabilitation scenario 1.a.

3.1.2 Case 2: Sandwich panel wall system

In this case, the initial heat transfer coefficient reached $U=0.36 \text{ W/m}^2\cdot\text{K}$. After the rehabilitation process, this value improved to $U=0.156 \text{ W/m}^2\cdot\text{K}$.

Table 2: Thermal resistances of layers in sandwich panel-based wall system

[mm]	Material	λ [W/mK]	R [m ² K/W]
Initial wall system			
	Thermal contact resistance*		0.13
0.5	SW panel (PUR) steel sheet	50	0
60	SW panel (PUR) insulation	0.023	2.609
0.5	SW panel (PUR) steel sheet	50	0
	Thermal contact resistance*		0.04
61	Whole component		2.779
Wall system after rehabilitation (additional layers)			
30	Metal rails Ω 30mm, h50, d35/2.5 S235	4.273	0.234
0.5	SW panel (PUR) steel sheet	50	0
80	SW panel (PUR) insulation	0.023	3.478
0.5	SW panel (PUR) steel sheet	50	0
	Thermal contact resistance*		0.04
172	Whole component		6.408

* Thermal contact resistances according to DIN EN ISO 6946 [9] for the U-value calculation. $R_{si}=0,25$ and $R_{se}=0,04$ according to DIN 4108-3 [10] were used for moisture proofing and temperature profile.

3.1.3 Case 3: Liner tray wall system

Table 3: Thermal resistances of layers in liner tray wall system

[mm]	Material	λ [W/mK]	R [m ² K/W]
Initial wall system			
	Thermal contact resistance*		0,13
0.75	Liner tray sheet	50	0
0.25	Vapor barrier	0.17	0,001
100	Mineral wool	0.032	3.125
20	Trapezoidal steel sheet**	10	0,002
	Thermal contact resistance*		0.04
121	Whole component		3,298
Wall system after rehabilitation (additional layers)			
80	Sandwich panel (PUR)	0.025	3.168
	Thermal contact resistance*		0.04
181	Whole component		6.465

* Thermal contact resistances according to DIN EN ISO 6946 [9] for the U-value calculation. $R_{si}=0.25$ and $R_{se}=0.04$ according to DIN 4108-3 [10] were used for moisture proofing and temperature profile.

** Removed layer according to the rehabilitation scenario

Before rehabilitation, the heat transfer coefficient was $U=0.3 \text{ W/m}^2\cdot\text{K}$. The final version of the envelope value reached $U=0.155 \text{ W/m}^2\cdot\text{K}$.

3.2 Assessment of the roof envelope systems

3.2.1 Case 4: Built-up roof system I

Table 4: Thermal resistances of layers in built-up roof system I

[mm]	Material	λ [W/mK]	R [m ² K/W]
Initial wall system			
	Thermal contact resistance*		0.13
20	Internal trapezoidal steel sheet	10	0.002
0.25	Vapor barrier	0.17	0.001
100	Mineral wool	0.032	3.125
45	External trapezoidal steel sheet**	10	0.005
	Thermal contact resistance*		0.04
101,25	Whole component		3.273
Wall system after rehabilitation (additional layers)			
0.4	SW panel (PUR) steel sheet	50	0
79.2	SW panel (PUR) insulation	0.025	3.168
0.4	SW panel (PUR) steel sheet	50	0
	Thermal contact resistance*		0.04
18,125	Whole component		6.441

* Thermal contact resistances according to DIN EN ISO 6946 [9] for the U-value calculation. $R_{si}=0.25$ and $R_{se}=0.04$ according to DIN 4108-3 [10] were used for moisture proofing and temperature profile.

** Removed layer according to the rehabilitation scenario 4.a.

Two rehabilitation scenarios have been considered for this system: the additional sandwich panel is fastened on the external trapezoidal sheet or, the trapezoidal steel sheet is removed, and the sandwich panels is placed on the initial insulation layer. The overall heat transfer coefficient for the initial set-up reached a value of $U=0.306$ W/m²*K. After the rehabilitation process, this value reached $U=0.155$ W/m²*K.

3.2.2 Case 5: Sandwich panel roof system

Table 5: Thermal resistances of layers in sandwich panel roof system

[mm]	Material	λ [W/mK]	R [m ² K/W]
Initial wall system			
	Thermal contact resistance*		0.13
0.5	Internal steel sheet	50	0
80	Thermal insulation (PUR)	0.17	0.001
0.6	External steel sheet	0.032	3.125
	Thermal contact resistance*		0.04
81.1	Whole component		4,500
Wall system after rehabilitation (additional layers)			
30	Metal rails Ω 30mm, h50, d35/2,5 S235	4.273	0.234
80	Sandwich panel (PUR)	0.025	3.168
	Thermal contact resistance*		0.04
191.1	Whole component		6.946

* Thermal contact resistances according to DIN EN ISO 6946 [9] for the U-value calculation. $R_{si}=0.25$ and $R_{se}=0.04$ according to DIN 4108-3 [10] were used for moisture proofing and temperature profile.

Before the rehabilitation, the initial roof system had a thermal coefficient value of $U=0.276$ W/m²*K. After this value was improved to $U=0.144$ W/m²*K. Due to the combination of double polyurethane

(PUR) insulation elements, this system has slight better insulation properties then a mineral wool with PUR addition.

3.2.3 Case 6: Built-up roof system II

Table 6: Thermal resistances of layers in built-up roof system II

[mm]	Material	λ [W/mK]	R [m ² K/W]
Initial wall system			
	Thermal contact resistance*		0.13
0.75	Roof liner tray	10.00	0
0.25	Vapor barrier	0.17	0.001
70	Thermal insulation Rockwool	0.035	2.00
1	Steel space bar	0.13	0.03
50	Thermal insulation Rockwool	0.035	1.429
20	Trapezoidal steel sheet**	10.00	0.002
	Thermal contact resistance*		0.04
142	Whole component		3.594
Wall system after rehabilitation (additional layers)			
100	Thermal insulation Rockwool	0.035	2.857
1.5	Waterproofing membrane	0.16	0.009
1.5	Waterproofing membrane***	0.16	0.009
	Thermal contact resistance*		0.04
245	Whole component		6.470

* Thermal contact resistances according to DIN EN ISO 6946 [9] for the U-value calculation. $R_{si}=0.25$ and $R_{se}=0.04$ according to DIN 4108-3 [10] were used for moisture proofing and temperature profile.

** Removed layer according to the rehabilitation scenario

*** Layers are placed on top of the additional insulation layer

For this system, the initial heat transfer coefficient was $U=0.279$ W/m²*K and was improved to $U=0.155$ W/m²*K.

3.2.4 Case 7: Deep corrugated trapezoidal roof system

Table 7: Thermal resistances of layers in deep corrugated trapezoidal roof system

[mm]	Material	λ [W/mK]	R [m ² K/W]
Initial wall system			
	Thermal contact resistance*		0,13
0,2	Internal high rib steel sheet	50	0
120	Thermal insulation Rockwool	0,035	3,429
1,5	Waterproofing membrane**	0,16	0,009
1,5	Waterproofing membrane**	0,16	0,009
	Thermal contact resistance*		0,04
81,1	Whole component		3,587
Wall system after rehabilitation (additional layers)			
100	Thermal insulation Rockwool	0,035	2,857
1,5	Waterproofing membrane	0,16	0,009
1,5	Waterproofing membrane***	0,16	0,009
	Thermal contact resistance*		0,04
191,1	Whole component		6,445

* Thermal contact resistances according to DIN EN ISO 6946 [9] for the U-value calculation. $R_{si}=0.25$ and $R_{se}=0.04$ according to DIN 4108-3 [10] were used for moisture proofing and temperature profile.

** Removed layer according to the rehabilitation scenario.

*** Layers are placed on top of the additional insulation layer.

The final roof system has similar thermal properties with the built-up 2 option. The total thickness of the insulation is 120 cm initially, leading to a U-value of $U=0.279 \text{ W/m}^2\text{K}$. After adding an extra 10 cm mineral wool insulation layer, the final thermal coefficient value is $U=0.155 \text{ W/m}^2\text{K}$.

3.3 Energy evaluation

As stated above, the overall thermal efficiency was evaluated using the online tool Ubakus. Table 8 shows the final values for each system before and after the rehabilitation process.

Table 8: Overall U-values for systems

Analysed solution	Envelope system	U [W/ m ² K]	U [W/ m ² K]	R [m ² K/W]	R [m ² K/W]
		-initial-	-upgrade-	-initial-	-upgrade
Case 1a	Built-up wall system (option A)	0.303	0.155	3.296	6.465
Case 1b	Built-up wall system (option B)	0.303	0.155	3.296	6.465
Case 2	Sandwich panel wall system	0.360	0.156	2.779	6.408
Case 3	Liner tray wall system	0.300	0.150	3.298	6.465
Case 4a	Built-up roof system 1 (option A)	0.306	0.155	3.273	6.441
Case 4b	Built-up roof system 1 (option B)	0.305	0.155	3.273	6.441
Case 5	Sandwich panel roof system	0.276	0.144	4.500	6.946
Case 6	Built-up roof system 2	0.279	0.155	3.594	6.470
Case 7	Deep corrugated trapezoidal roof system	0.279	0.155	3.587	6.445

* The values were calculated "in-field" of the envelope system and not for the whole model

To evaluate the energy consumption, an industrial hall model 10 meters by 30 meters, with no openings has been considered (Figure 15). The simulation was carried out using the built-in Energy Evaluation Design tool of Graphisoft Archicad 21 [8].

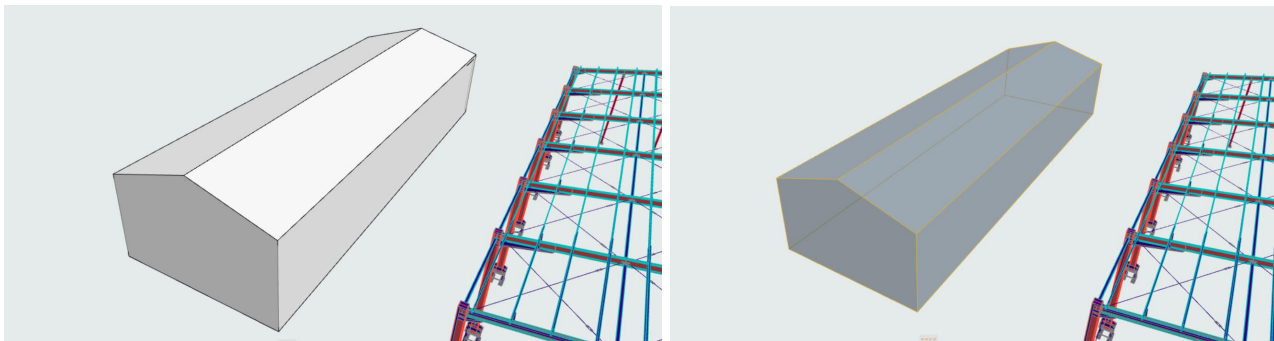


Figure 15. Industrial hall building model (left) and the evaluated thermal block (right)

Considering the resulted thermal coefficient values, two cases have been considered for the energy evaluation: built-up wall with built-up roof and sandwich panel wall with sandwich panel roof. Furthermore, the following parameters were used as input for the energy balance calculation:

- Human heat gain: 100W per capita;
- Service hot-water load: 60l/day per capita;
- Humidity load: 2g/day per sqm;
- Space usage: 6264 hours/year;
- Internal temperature range: 14°C -18°C;
- Heating and cooling: 60000 BTU conditioning system, 66 kWh heating capacity and 57.4 kWh cooling capacity, with control sensors.

Figure 16 shows the energy results for the built-up wall and roof system, while Figure 17 present it for sandwich panel system.

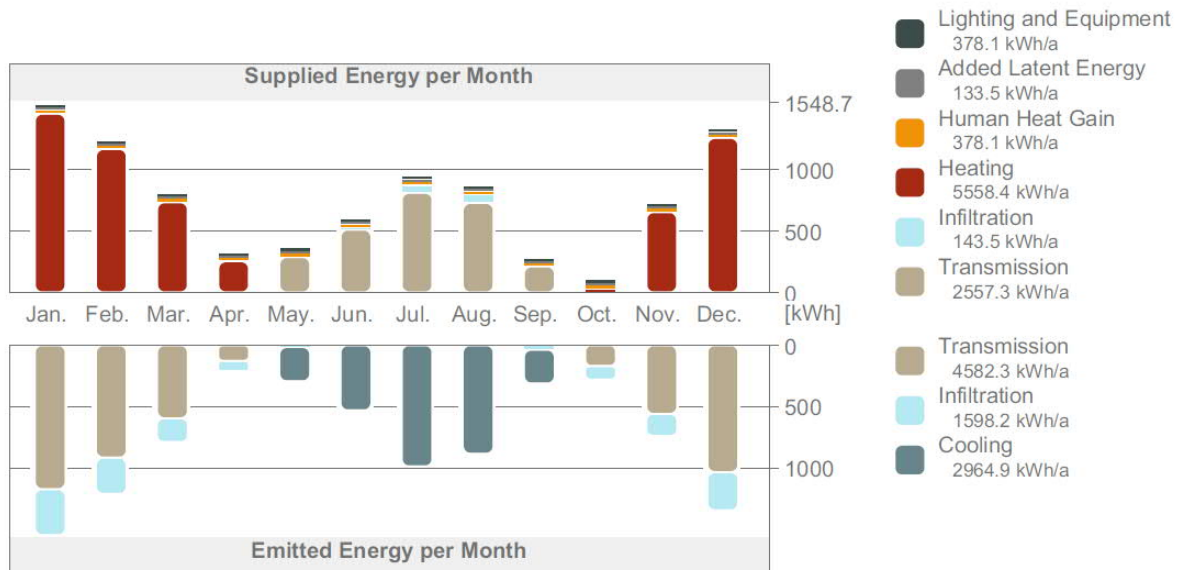


Figure 16: Energy results for built-up wall with built-up roof

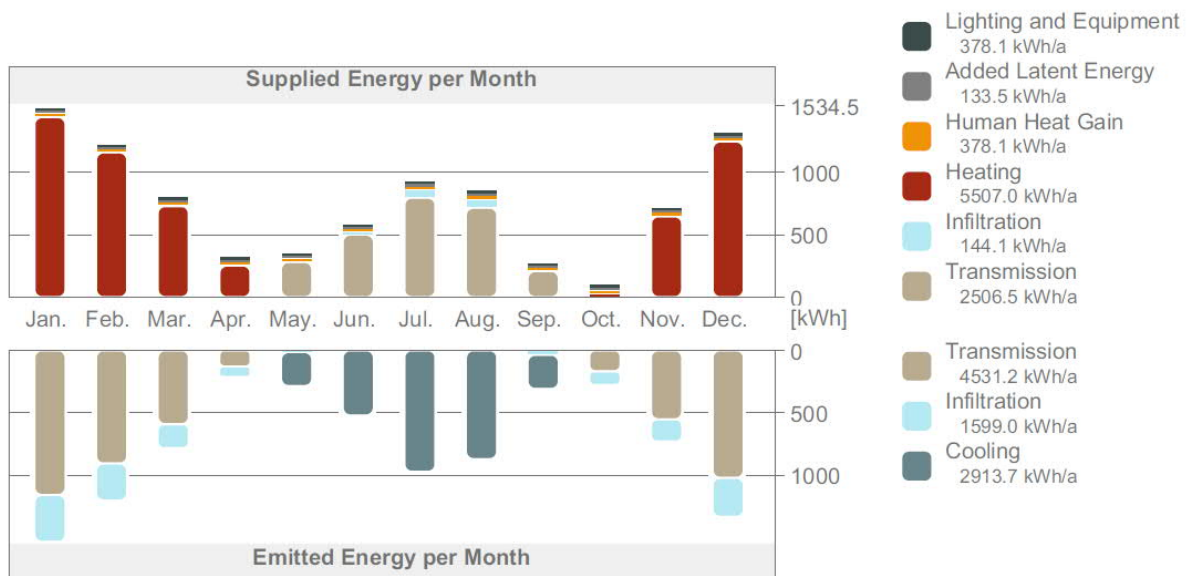


Figure 17: Energy results for sandwich panel wall with sandwich panel roof

4. Environmental benefits

The Life Cycle Assessment (LCA) has been calculated using openLCA software [11] together with Ecoinvent 3.6 database [12]. The evaluation of the environmental impact follows the rules of ISO 14044 [13], EN 15804 [14] and EN 15978 [15]. The benefits beyond the system boundary were reported separately, as claimed by CEN/TC 350 methodology [16] for the approach of accounting of recycling in LCA. The indicator for the environmental performance of the rehabilitated solutions was considered Global warming potential (GWP 100).

4.1 System boundary

- The declared unit is 1m² of rehabilitated envelope solution; the averaging was computed based on an envelope of a 30 x 10 m industrial hall (426.45 m² of wall envelope and 357.49 m² of roof envelope).
- The operational lifetime of each rehabilitation solution considered in the assessment was 25 years.
- Flows related to the production of heavy equipment, transport vehicles, production machines, construction of production plants are excluded from current assessment.

4.2 Life Cycle Stages

Product stage (A1-A3)

The Product Stage includes modules A1 (Raw materials extraction, processing of secondary material input), A2 (Transport to the manufacturer) and A3 (Manufacturing). These modules consider the extraction and processing of steel, rockwool, PUR insulation, hydro insulation membrane, energy consumption for these processes, the transportation of raw materials to the manufacturing plant, the manufacture of products and packaging.

Construction stage (A4-A5)

This stage refers to modules A4 (Transport to the building site) and A5 (Installation).

In this study case, the model considered road transport for the transportation of the products from the production gate to the building site, where they would be installed. The road distance weighed in the study was 100 km for all types of products, using Euro 6 trucks with a capacity of utilization of 85% (including empty runs) for sandwich panels, hydro insulation membrane, steel sheets and 40% (including empty runs) for rockwool (due to gross density of products transported).

For the installation module, in this study case was considered that 2% of sandwich panels, hydro insulation membrane and rockwool derived as waste from the installation of the construction materials and as such, additional production of materials was taken into consideration to compensate for losses. Loosed materials were sent to landfill but the waste derived from packaging (polyethylene film, cardboard, wooden pallets) was considered to be 100% collected and transformed into recovered material (as elementary components). Recycling potential resulted from packaging recovery was not quantified in module D. In the installation module was also considered transport of equipment and workers for the installation process (30 km), the dismantle of exterior steel sheet (in cases 1a, 3, 4a) or of the existing hydro insulation membrane (case 7), as well as diesel consumption from different heavy equipment (manlifts, forklifts).

Use stage (B1-B7)

In Use stage are analysed the following modules: B1 (Use), B2 (Maintenance), B3 (Repair), B4 (Replacement), B5 (Refurbishment), B6 (Operational Energy Use), B7 (Operational Water Use).

As the operational lifetime of industrial hall (on which the averaging for the declared unit was based) considered in the study was 25 years and the lifetime of each construction material used in the rehabilitation solutions is min. 30 years, no maintenance, repair, replacement or refurbishment were considered in the environmental analysis. The impact of the rehabilitation solutions in this stage is zero since after the completion of the installation, the envelope does not require additional technical operations and there are no emissions to occur to the environment during use stage. Moreover, operational energy use and operational water use are characteristic to entire buildings.

End-of-life (C1-C4)

The End-of-life is subdivided into 4 modules, which represent C1 (De-construction/Demolition), C2 (Transport), C3 (Waste processing) and C4 (Disposal).

In this study case the end-of-life scenario for each one of the seven cases studied involved deconstruction/dismantling of the materials which constituted the rehabilitation solutions previously installed. Table 9 shows the end-of-life scenarios considered in the study case for each component of rehabilitation solutions analysed. For example, for sandwich panels, it was considered that 90% are reused and from the remaining sandwich panels, 90% of the steel sheets are recovered for recycling (7.03% of the total mass of 1m² sandwich panel).

Table 9. End-of-life scenarios for products used in envelopes rehabilitation [17][18][19]

Component	End-of-life scenario		
	Reuse	Recycle	Landfill
Sandwich panels	90%	7%	3%
Metal rails (spacers), screws	0%	96%	4%
Steel sheet	0%	89%	11%
Rockwool	0%	0%	100%
Hydro insulation membrane	0%	0%	100%

In the Demolition/De-construction module it was also considered transport of equipment and workers (30 km), diesel consumption from different heavy equipment (manlifts, forklifts, wheel loader, hydraulic scrap shear [17][20]).

The deconstruction process of sandwich panels, in order to reuse them, follows the reverse assembling process, therefore the emissions in C1 module equals emissions in A5 module for these specifically component.

Transport of residual materials deriving from deconstruction and demolition to the waste processing or landfill is included in C2 module. A transport distance of 50 km has been considered in either way. The waste processing covers handling for reuse, recycling and disposal.

Benefits and loads beyond the system boundary (D)

Module D reflects the reuse and/or recycling potentials of construction materials, expressed as net impacts and benefits [21][22], by integrating them in a life cycle of a new product or by developing into a secondary source materials.

In this paper data for Module D is based on scenarios considering current practices and current rates of materials recycling [17][18][19]. The calculation model used for the assessment of Module D is based on an innovative calculation model, compatible with the methodology of the EN 15804 Product Environmental Footprint (European Commission, 2018) [14] standard and the World Steel Association (2017) approach [24]. The calculated impact involving potential environmental credits or burdens generated by future lifecycles is based on the impacts of the reuse and the recycling of the materials jointly operated. The calculation is based on the inputs and outputs of recycled and reused materials, on the impact of the virgin material production and the impact of theoretical pure recycling [17].

4.3 Life Cycle Assessment results

The environmental impact of the assessment was expressed using GWP as a pointer. Table 10 outlines the greenhouse gas (GHG) emissions for each scenario of rehabilitated wall systems.

Table 10. LCA results of the rehabilitated envelope wall systems

Scenario	Built-up wall system (case 1) [kg CO ₂ e/m ²]		Sandwich panels wall system (case 2) [kg CO ₂ e/m ²]	Liner tray wall system (case 3) [kg CO ₂ e/m ²]
	Solution a	Solution b		
Environmental impact (A-C)	35.06	34.37	37.59	35.06
-Production stage (A1-A3)	31.05	31.05	33.80	31.05
-Construction stage (A4-A5)	1.86	1.29	1.54	1.86
-Use stage (B6)	0	0	0	0
-Demolition / deconstruction stage (C1-C4)	2.15	2.03	2.25	2.15
Loads and benefits (D)	-33.82	-27.19	-28.52	-33.82

According to the results, smallest environmental impact is shown by the case when on a built-up wall system is installed a new sandwich panel (34.37 kg CO₂ e/m² – case 1b), without removing any other components from the existing envelope. Although in the production stage, Case 1a, 1b and Case 3 record the same level of emissions (31.05 kg CO₂ e/m²), due to the construction and de-construction stages, where additional effort is required for dismantling of the external steel sheet of the existing envelope, the total environmental impact (stages A-C) is shown in Case 1b. The highest rate of emissions (37.59 kg CO₂ e/m² – case 2) is registered when on an existing envelope consisting in sandwich panels are installed metal rails (spacers) and an additional layer of sandwich panels.

Regarding the benefits (reflected in the assessment as negative values) calculated in Module D, the highest potential benefits appear in cases 1a and 3 (33.82 kg CO₂ e/m²), due to the fact that in these case scenarios, along with the reuse of the sandwich panels, the rehabilitation solution requires the dismantling of an existing steel sheet which is recycled.

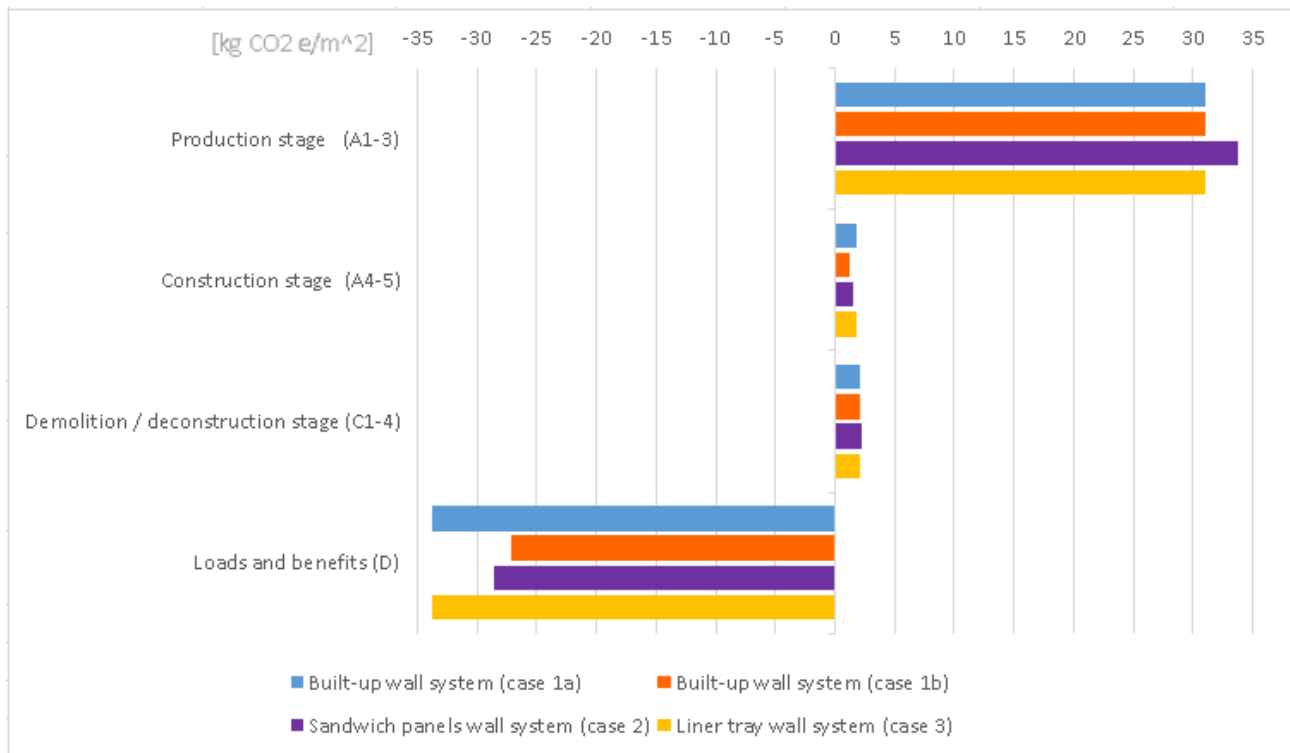


Figure 18. LCA results of the rehabilitated wall systems including loads and benefits beyond the system boundary

Figure 18 shows comparative LCA results for the assessed rehabilitation solution in case of wall envelopes. It can be seen that benefits and loads beyond the system boundary are not aggregated with the life cycle impacts (Modules A to C), as provided by the CEN/TC 350 methodology.

Table 11. LCA results of the rehabilitated envelope roof systems

Scenario	Built-up roof system I (case 4) [kg CO ₂ e/m ²]		Sandwich panels roof system (case 5) [kg CO ₂ e/m ²]	Built-up roof system II (case 6) [kg CO ₂ e/m ²]	Deep corrugated trapezoidal roof system (case 7) [kg CO ₂ e/m ²]
	Solution a	Solution b			
Environmental impact (A-C)	35.06	34.37	37.59	28.38	28.43
-Production stage (A1-3)	31.05	31.05	33.80	23.36	23.36
-Construction stage (A4-5)	1.86	1.29	1.54	3.11	3.13
-Use stage (B6)	0	0	0	0	0
-Demolition / deconstruction stage (C1-2)	2.15	2.03	2.25	1.91	1.95
Loads and benefits (D)	-34.47	-27.19	-28.52	-6.76	0

The emissions of scenarios which include the rehabilitation of roof envelope systems are expressed in Table 11. As the results show, smallest environmental impact is shown by the case when, on the built-up wall system II, the external steel sheet of the existing roof is removed and on top of the existing envelope a new layer of rockwool and two layers of hydro insulating membrane are installed. Despite the additional workload of this case scenario, reflected in the construction stage emissions, the total LCA results ($28.38 \text{ kg CO}_2 \text{ e/m}^2$ – case 6) are the smallest among the other rehabilitation solutions for roofs, in behalf of the relative small environmental impact in the production stage ($23.36 \text{ kg CO}_2 \text{ e/m}^2$) of the Case 6's components, in comparison with the construction materials integrated by the other case scenarios ($31.05\text{-}33.80 \text{ kg CO}_2 \text{ e/m}^2$).

The highest potential benefits of rehabilitated roof case scenarios, calculated in Module D, analogous with the benefits of retrofit wall solutions, appears in case 4a ($34.47 \text{ kg CO}_2 \text{ e/m}^2$), due to the fact that also in this case scenario, along with the reuse of the sandwich panels, the rehabilitation solution requires the dismantling of an existing steel sheet which is recycled and recorded as a benefit for the environment. On the opposite side is registered Case 7 with no potential benefits figured in Module D, as a result of generating 100% waste materials in the end-of-life.

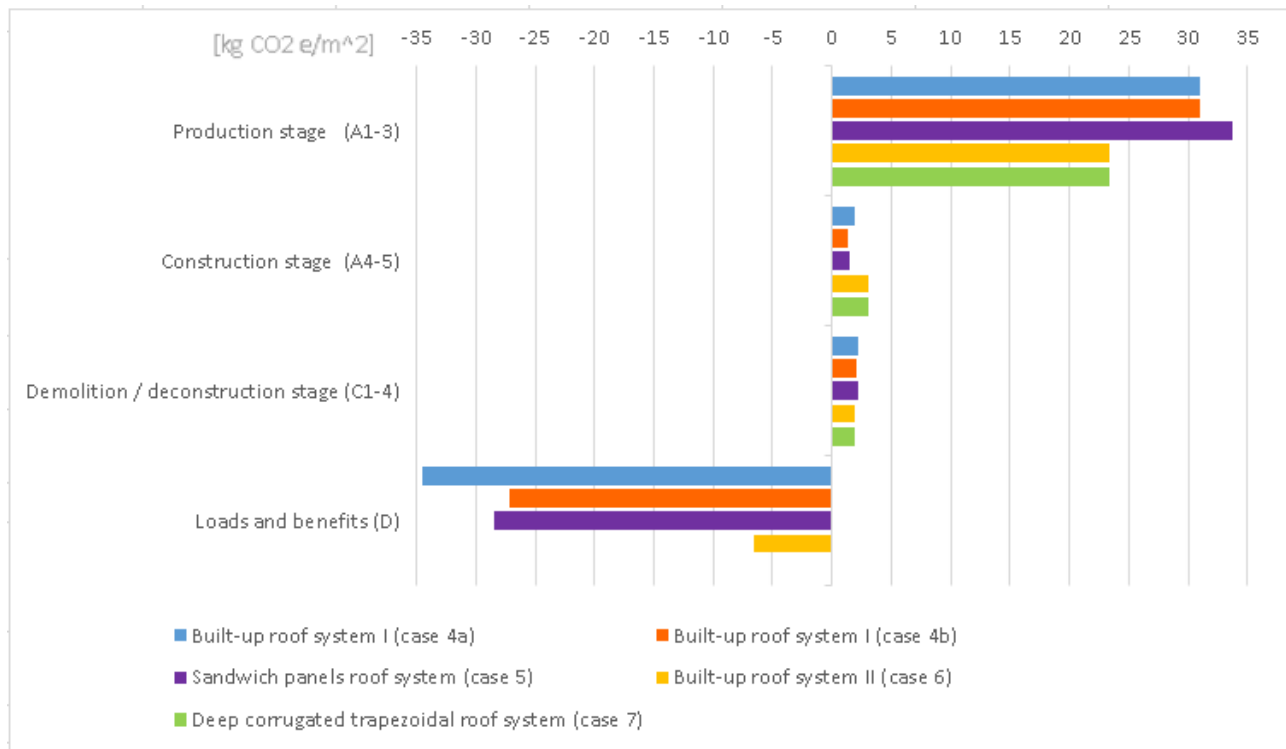


Figure 19. LCA results of the rehabilitated roof systems including loads and benefits beyond the system boundary

5. Economic assessment

The calculation of economic indicators is based on the same scenarios and modules as in the LCA analysis, referring to envelope rehabilitation solutions, to which were associated time and financial costs. The assessment of the economic performance of studied cases follows the rules described in EN 16627 [25][26].

5.1 Assessed scenarios of the economic impact

Recovered materials and recycled steel scrap can generate earnings as benefits and savings. Potential cost savings includes revenues for recycled steel (earnings from the sold steel scrap) and revenues from the sold sandwich panels. The returns considered in case of the sold steel scrap were of 180 euro/ton (the value represents the price of auctioned steel scrap in Romania at the moment of the assessment), while the gains from the sold sandwich panels were calculated at a value of 11.5 euro/m².

As considered in the LCA, the impact of the rehabilitation solutions in the use stage is zero as a result of the fact that after the completion of the installation, the envelope does not require additional technical operations, therefore, the costs allocated to Module B are also zero.

5.2 Life Cycle Costs results

The results of the life cycle cost assessment show that the economic impact in the production stage (Modules A1-A3) varies from 20 to 23 euro/m² in case of envelope systems for walls and from 20 to 42.08 euro/m², in case of envelope systems for roofs. The cost difference for roof envelope systems in the production stage is due to a significant cost between sandwich panels and single-ply membrane.

Table 12: LCC results of the rehabilitated envelope wall systems

Scenario	Built-up wall system (case 1) [euro/m ²]		Sandwich panels - wall system (case 2) [euro/m ²]	Liner tray wall system (case 3) [euro/m ²]
	Solution a	Solution b		
Economic impacts (A-C)	45.34	44.84	48.34	45.34
-Production stage (A1-3)	20	20	23	20
-Construction stage (A4-5)	12.97	12.47	12.97	12.97
-Use stage (B6)	0	0	0	0
-Demolition / deconstruction stage (C1-2)	12.37	12.37	12.37	12.37
Loads and benefits (D)	-11.31	-10.51	-10.68	-10.51
Total costs (including potential savings)	34.03	34.33	37.66	34.83

Life cycle costs results of the assessment for all life cycle stages, including potential savings, are given in Table 12 (for rehabilitated wall systems) and Table 13 (for rehabilitated roof systems), where potential savings are reflected as negative values.

Table 13: LCC results of the rehabilitated envelope roof systems

Scenario	Built-up roof system I (case 4) [euro/m ²]		Sandwich panels roof system (case 5) [euro/m ²]	Built-up roof system II (case 6) [euro/m ²]	Deep corrugated trapezoidal roof system (case 7) [euro/m ²]
	Solution a	Solution b			
Economic impacts (A-C)	50.04	49.54	53.04	60.80	61.30
-Production stage (A1-3)	20	20	23	42.08	42.08
-Construction stage (A4-5)	17.67	17.17	17.67	16.42	16.92
-Use stage (B6)	0	0	0	0	0
-Demolition / deconstruction stage (C1-2)	12.37	12.37	12.37	2.29	2.29
Loads and benefits (D)	-11.31	-10.51	-10.68	-0.80	0.00
Total costs (including potential savings)	38.73	39.03	42.36	60.00	61.30

According to the results, highest LCC (modules A-C) is shown by Case 2 - the Sandwich Panel - based Wall System rehabilitation (48.34 €/m²) and by Case 7 - the Deep Corrugated Trapezoidal Roof System rehabilitation (61.30 €/m²).

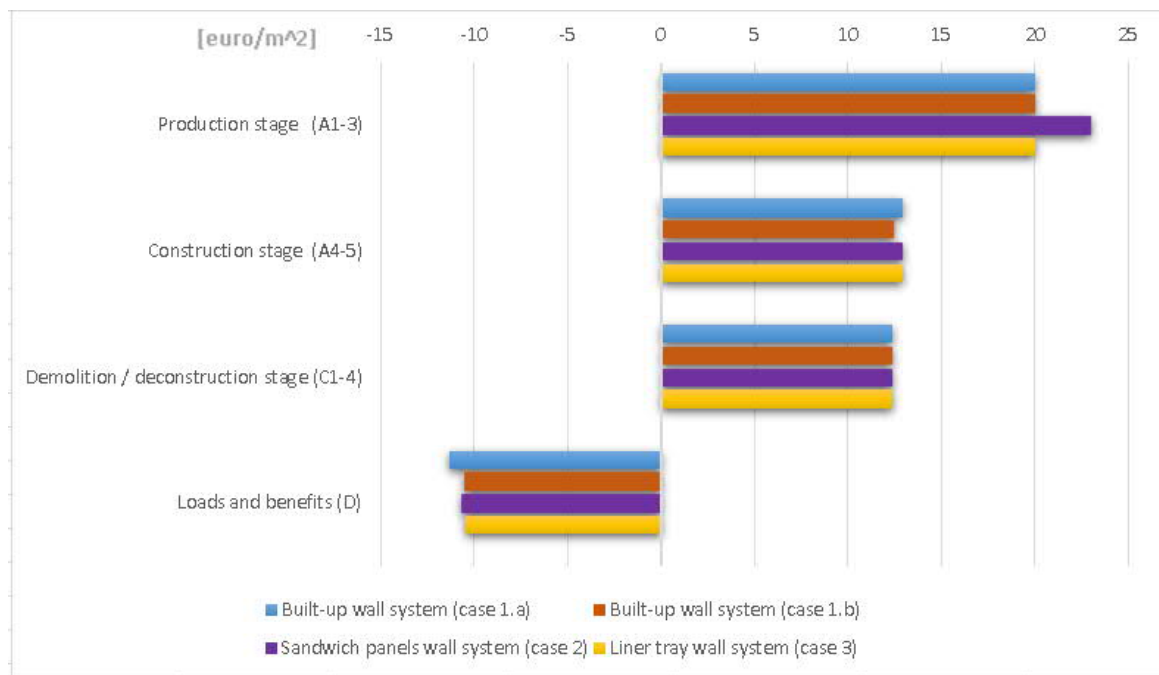


Figure 20. LCC results of the rehabilitated Envelope Wall Systems, including potential savings

The lowest LCC for rehabilitated wall systems (44.84 €/m²) is registered by the cases 1.b (Built-up Wall System) when the external steel sheet of the existent envelope it is not removed before installing the new sandwich panel, avoiding as such additional workload. In case of rehabilitated roof systems, the lowest LCC (49.54 €/m²) is shown in Case 4.b (Built-up Roof System I).

Comparative LCC results of each case scenario are shown in Figure 20 (for rehabilitated wall systems) and Figure 21 (for rehabilitated roof systems). When considering the loads and benefits from Module D only, the highest savings (11,31 euro/m² – case 1a and 4a) come when sandwich panels are deconstructed and sold for a future reuse in the end-of-life, along with the earnings gained from the sold steel scrap resulted from the recycling of steel sheets.

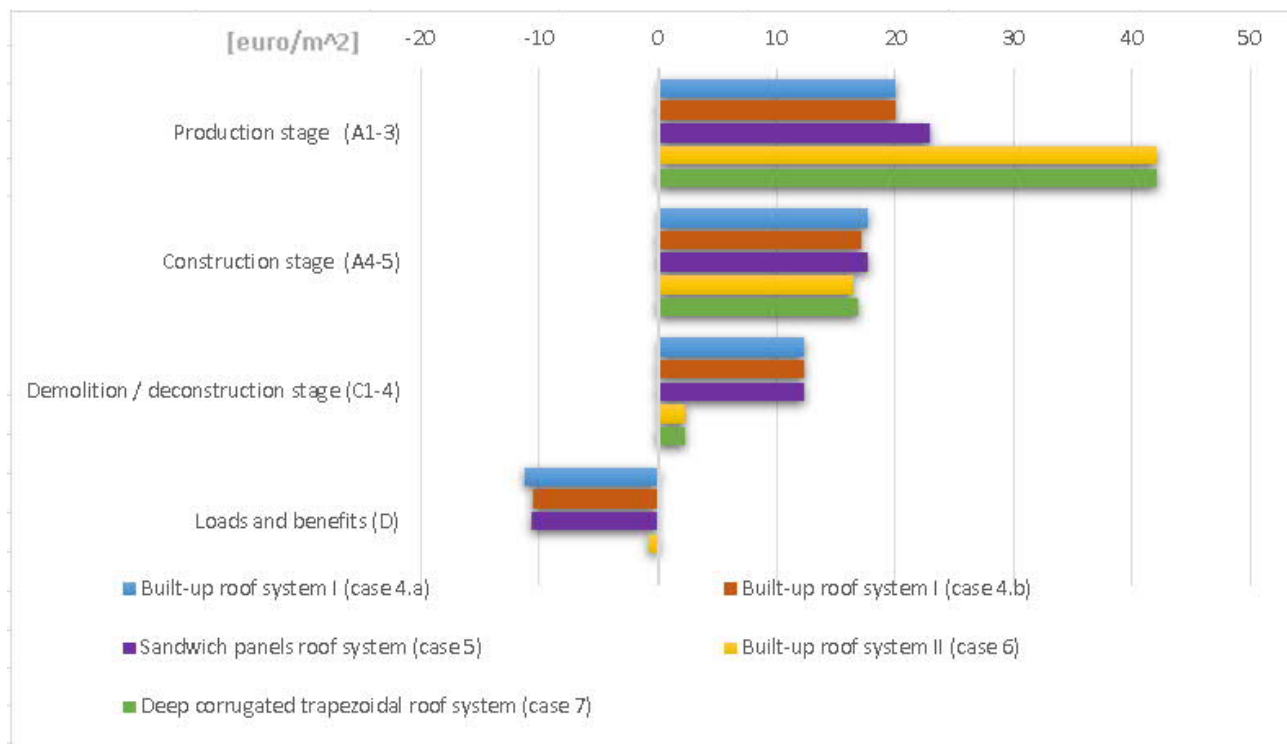


Figure 21. LCC results of the rehabilitated Envelope Roof Systems, including potential savings

6. Fire safety

The fire behaviour of the novel hybrid systems was not tested within the project. Instead, information describing the fire behaviour of the individual components is compiled below.

6.1 Fire behaviour of profiled panels

The fire behaviour of profiled panels is dependent on the profile, the organic coating and any laying on thermal insulation. Essentially, the fire behaviour of profiled panels is based on the fire behaviour of the organic coating or metallic coating.

6.1.1 Fire behaviour of organic coatings

The fire behaviour of organic coatings is determined in the SBI test on a flat sheet sample. Organic surface coatings of the same family with lower mass per unit area and lower PCS value are covered by the test result.

6.2 Fire resistance of profiled panels

Profiled metal panels cannot achieve a fire resistance classification without special measures. Without testing, it can only be established that it is a non-load-bearing construction, which essentially consists of non-combustible building materials. However, as a construction and in combination with other building products, profiled metal panels can still be used to construct fire-resistant building components.

6.2.1 Liner Tray Wall System W90

As a liner tray wall construction according to a general building authority test certificate, profiled panels can achieve fire resistance class W90-A according to DIN 4102-3. The fire resistance is mainly achieved by separating the components. The supporting structure (liner tray) must be protected from the continuous elements (cover shell) by strips of fire-resistant material, e.g. calcium silicate boards, against direct flame impingement and high temperatures.

6.3 Fire behaviour and fire resistance of sandwich panels

6.3.1 Sandwich panels with PU core

At European level, fire behaviour is assessed according to EN 14509. The SBI test must be performed without covering the cut edges of the test specimen. A small burner test is also required. Due to the flame treatment of the open edges, the classification of the fire behaviour contains the addition "all end uses". The fire behaviour of PU sandwich panels depends largely on the foam system. PU sandwich elements are considered to be flame-retardant or normally flammable. The classification can be from B-s2, d0 to E-d2 (according to EN 13501). The explicit fire behaviour of the sandwich type must be specified by the manufacturer, e.g. in the declaration of performance and the CE marking.

Flame resistant and normally inflammable PU sandwich elements do not contribute to the maintenance of the fire with. After removing the flame, the Fire. The results of the tests show that PU insulation materials in general neither burning nor drip off not burning.

Depending on the properties of the core material, PU sandwich panels resist fire attack to varying degrees. The fire resistance depends, among other things, strongly on the proportion of organic components or the use of flame retardants. In any case, the construction must be tested for fire resistance in order to classify it.

6.3.2 Sandwich panels with mineral wool core

Sandwich elements with a mineral wool core are basically tested at European level according to the same standards as PU sandwich elements. Mineral wool sandwich elements are classified in class A2-s1, d0, as non-combustible building materials according to EN 13501. The type and quantity of the organic and thus combustible PU adhesive (1-K or 2-K / filled or unfilled) used, which is necessary for the connection of the metal cover shells with the mineral wool core, is the decisive classification criterion. For these elements, therefore, in addition to the condensing value and furnace testing of the for combustible substances required SBI test necessary.

After the test in a fire shaft, mineral wool sandwich panels visibly show the burnt organic residues of the adhesive on the side exposed to the fire after removing the steel face sheets. It can be seen that more than 50 % of the sample length shows no discoloration or fire propagation.

Depending on the properties of the core material, mineral wool sandwich panels resist fire attack to varying degrees. The fire resistance depends, among other things, strongly on the proportion of organic components or the use of flame retardants. In any case, the construction must be tested for fire resistance in order to classify it.

7. Sound insulation

Sound insulation tests were carried out on hybrid system (case 3: liner tray wall system and sandwich panel). The outer trapezoidal steel sheet is removed from the existing wall envelope system and a sandwich panel is installed over the remaining original built-up wall system. The intermediate construction was either filled with mineral wool inlay or remained unfilled.

The following assumptions apply to the type tests performed:

- The liner tray profile is completely filled with mineral wool insulation with a density of at least 50 kg/m³.
- When fastening the sandwich panels or the intermediate construction, the maximum fastening distance specified in the test certificate of the cassettes must not be exceeded.
- Only connecting and fastening materials of lightweight metal construction approved by the building authorities are to be used.

7.1 Influence of the core material of the sandwich element on the sound insulation

The test set-up consists of a 130 mm high steel liner tray profile with directly attached steel sandwich panels with polyurethane and mineral wool insulation core.

Table 14: Change of the sound reduction index based on a changed core insulation

Thickness sandwich panel [mm]	Core material	R _w [dB]
80	PU	46
	MW	47

From the results it can be seen that with these relatively small component thicknesses of the sandwich elements, the influence of the core material and an associated increase in weight do not result in any significant improvement in sound insulation. This is due to the general stiffness of the outer shell of sandwich elements.

7.2 Influence of a distance construction on the sound insulation

The previously tested wall constructions were varied with regard to the attachment of the sandwich elements to the cassette profiles. The following results were tested with a fastening of the sandwich elements on an intermediate construction with 40 mm height. The intermediate space was filled with mineral wool insulation with a density of at least 50 kg/m³.

Table 15: Change of the sound insulation dimension through a distance construction

Thickness sandwich panel [mm]	Core material	R _w [dB]
80	PU	50
	MW	51

The results show that the installation of an intermediate construction contributes to an improvement of the sound insulation level by 4 dB. The influence of the core material is also 1 dB in this test setup. The acoustic improvement of the modified wall configuration by 4 dB results on the one hand from changed stiffness ratios and on the other hand from the increased weight of the overall construction.

7.3 Influence of the intermediate insulation on the sound insulation properties

As a reference test, the wall construction with a polyurethane sandwich panel without mineral wool insulation in the intermediate construction was tested.

Table 16: Change of the sound insulation dimension by omitting an intermediate insulation

Thickness sandwich panel [mm]	Core material	R _w [dB]
80	PU	48

The result shows that dispensing with mineral wool insulation in the intermediate construction leads to a reduction of the sound insulation level by 2 dB. The result is due to the lower total weight of the construction. The changed stiffness due to the use of the intermediate construction leads to an improvement of the sound insulation value of 2 dB compared to direct fixing.

7.4 Influence of perforated cassette profiles on sound insulation

Improvements in room acoustics can be achieved by using perforated cassette profiles. The perforated cassette profiles were completely filled in one layer with mineral wool insulation. The sandwich elements were fixed to an intermediate construction. The intermediate space was filled with mineral wool insulation with a density of at least 50 kg/m³ or remained unfilled. The function of the vapour barrier in these wall constructions is taken over by the internal covering shell of the sandwich panel.

Table 17: Change of the sound insulation dimension based on a perforated liner tray profile

Thickness sandwich panel [mm]	Core material	Intermediate insulation	R _w [dB]
120	MW		41
	MW	40 mm	45
240	MW		47
	MW	40 mm	50

The results show that a construction with a perforated cassette profile with and without mineral wool insulation in the intermediate construction leads to sound insulation dimensions

between 41 and 50 dB, with simultaneous sound absorption via the cassette insulation. Compared to the classic design with a trapezoidal profile outer shell, this results in an improvement in the sound insulation level of up to 10 dB with the same geometries of the load-bearing components.

7.5 Sound absorption - Influence of the thickness of the sandwich panel

The hybrid construction has the following structure: liner tray profile 600 / 100 / 0.88 mm, hole proportion 17.9%, fully insulated, spacer profile 60 / 40 / 60 mm with 40 mm mineral wool insulation, mineral wool sandwich panel as cover shell with 120 mm and with 240 mm panel thickness. The influence of the element thickness on the sound absorption was investigated.

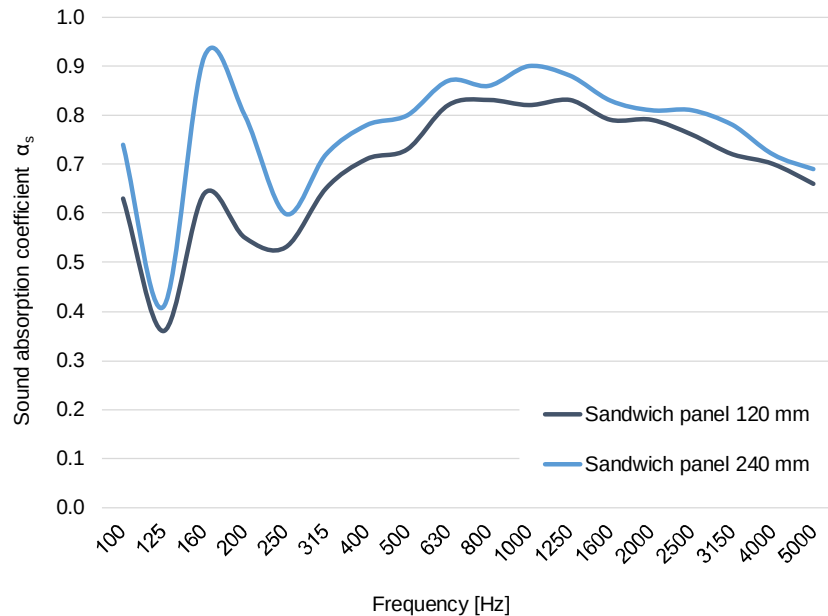


Figure 22. *Influence of the thickness of the sandwich panel on the sound absorption coefficient α_s in hybrid constructions*

The measurement result shows a more homogeneous course of the sound absorption curve. Due to the higher dead weight and the resulting change in resonance frequency, the hybrid construction with a 240 mm sandwich panel achieves higher values of sound absorption over the entire frequency band. The improvement of the sound absorption due to the doubling of the sandwich panel thickness can be estimated at about 10 %. Compared to the usual liner tray constructions, significantly higher sound absorption values are achieved, especially in the low frequency range.

8. Summary and conclusions

The need to update building's envelope to current standards of thermal performance appears more and more often lately. Consequently, the building envelope needs hybrid elements, which allow an easy adaption to new requirements, an effortless dismantling and, by any means, to ensure a future possible reuse of the components and recycling of the materials. The present assessment considered seven study-cases, where rehabilitation solution to classic envelope systems for industrial facilities were analysed in order to approach energy efficiency, environmental impact and costs.

The Life Cycle Assessment results showed that envelope rehabilitation solutions are a strategy that holds environmental benefits in extending the life cycle of buildings. According to the results, GHG emissions (modules A-C) fluctuate between 34.37 to 37.59 kg CO₂ e/m² in case of wall rehabilitation solutions and 28.38 to 37.59 kg CO₂ e/m² in case of roof rehabilitation solutions. Due to reuse and recycling high extent of the materials contained, the rehabilitation solutions showed potential environmental benefits roughly to the values recorded in A-C modules, such as 27.19 to 33.82 kg CO₂ e/m² in case of wall rehabilitation solutions. In case of roof rehabilitation solutions, there were registered cases where the emissions computed in D module were absent or very small (6.76 kg CO₂ e/m²), but in those cases, the environmental impact for modules A-C was the smallest among all cases (28.38-28.43 kg CO₂ e/m²).

When it comes to economic impact of the envelope rehabilitation solutions, costs vary (in A-C stages) from 44.84 €/m² to 48.84 €/m² in case of wall rehabilitation solutions and from 49.54 €/m² to 61.30 €/m² in case of roof rehabilitation solutions. Potential savings range between 10.51 and 11.31 €/m² in case of wall rehabilitation solutions and between 0 and 11.31 €/m² in case of roof rehabilitation solutions. As the results showed, environmental impact in construction and de-construction / demolition stages was negligible in comparison with the production stage, but as for economic impact, costs in construction and de-construction / demolition stages were as high as the costs in the production stage of even higher.

Although the rehabilitation solutions are difficult to reuse in the very same layer stratification as presented in this study case (due to perforations occurred through cladding fixing), these layers could be reused for another life cycle as interior layers in an envelope system.

Nonetheless, due to the large variation of materials and building practices, LCC and LCA calculations are recommended to be carried out on a case-by-case basis, as the results could differ significantly from the present study. Some reasons for obtaining differences in results are the lack of significant quality data for deconstruction, the burdens (energy consumption and costs) related to the transportation of construction materials and the fact that the value of reusable construction materials ranges from one country to another in the European market.

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