

# D5.2

## Catalogue of materials and systems



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# D5.2 Catalogue of materials and systems

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# 1 Introduction

This deliverable is the one of the final outputs of Task 5.3 *Toolbox of Materials, Connections, and Systems for Resilient Facades and Structures*, focuses on identifying the most suitable connections, systems, materials, and components for a set of representative European locations, including the MULTICARE demonstration sites.

The foundation for the Task 5.3 is laid out in *Deliverable 5.1: Multi-Criteria Framework for Resilient Components*, which defines a methodology for assessing the multi-hazard resilience of building systems and components. This deliverable also categorizes systems and components within the scope of Work Package 5.

Task 5.3 applies this assessment framework in a case study for one of the MULTICARE demonstration sites: Acerra, Italy. The study involves identifying feasible design options and evaluating their performance in terms of seismic resilience, heat resilience, circularity, and adaptability. By quantifying the multi-domain performance of different design solutions, the task supports informed decision-making and enables a comparative analysis of potential facade and structural systems.

The outcomes of Task 5.3 are presented in two key deliverables:

**Deliverable 5.2: Catalogue** This document compiles the results of the pre-evaluation of facade systems, detailing the input parameters and assessment methodologies used in the evaluation.

**Deliverable 5.3: Database** A digital interface designed to facilitate data processing, visualization, and user interaction.

The objective of Deliverable 5.2 is to demonstrate the assessment of alternative facade design according to the Multicare approach, which compare and utilizes different performance indicators, including seismic resilience, heat resilience, and circularity.

The document is structured as follows:

Section 2: Describes the procedure for selecting the nine design schemes for evaluation. This includes data collection on market-available facade systems, assigning different design concepts, and configuring materialization to prepare the schemes for assessment.

Section 3: Explains the evaluation methods and procedures for each design scheme across the three domains—seismic resilience, heat resilience, and circularity. This involves translating the information from Section 2 into the appropriate input parameters for domain-specific analysis, assigning extreme event or end-of-life scenarios, and obtaining quantifiable indicators for comparison.

Section 4: Presents the catalogue of evaluated facade systems, summarizing input attributes, providing 3D sketches of facade configurations, and displaying multi-domain assessment results using radar charts.

Section 6: Concludes by summarizing the catalogue development process and reflecting on whether the chosen indicators and methods successfully enable meaningful comparisons of facade systems across multiple domains.

## 2 Definition and Selection of Façade Systems for Performance Evaluation

This section outlines the procedure for defining and selecting façade systems to be evaluated in Section 3. The process is structured into four key steps:

### 2.1 Data Collection and Classification of Market-Available Façade Systems

In this step, facade materials, components, and systems available from the market are gathered and organized into an inventory. This classification serves as the basis for identifying the range of materials, components to be considered in the study.

### 2.2 Specification of Façade Geometrical Features

Material properties alone are insufficient to fully define a facade system. Therefore, geometric features—such as module dimensions and positioning relative to the building's structural frame—are specified in this step.

### 2.3 Evaluation and Rating of Material Combinations

Based on the developed inventory and geometric definitions, potential material combinations are preliminarily assessed. Combinations that align with various design intentions—such as feasibility, low cost, low carbon footprint, lightweight construction, or integration of specific technologies—are selected for further consideration.

### 2.4 Summary of Façade Systems for Performance Evaluation

As an outcome of Steps 2.1 to 2.3, nine façade schemes are developed to a level of preliminary design detail sufficient for performance evaluation. These schemes are presented along with a summary of their design specifications.

## 2.1 Data Collection and Classification of Market-Available Façade Systems

### **Preliminary data collection for façade system and material**

To facilitate the design requirements for all demo sites using façade typologies selection, it is essential to identify market-available solutions that address these design needs. We have compiled a comprehensive list of façade components, systems and materials, correlating their properties with existing performance data (Figure 1, Figure 2). This includes key parameters such as material properties, carbon footprint, and U-values etc. This information serves as a foundation for the preliminary selection of façade materials, ensuring an informed approach to achieving both functional and sustainable design objectives.



### Auxiliary System with Integrated Resilience Function

This study includes state-of-the-art components and products that provide auxiliary functions for climate control. For climatic loads, in addition to thermal protection by means of insulating and sealing, the protective function extends to climate control and regulation, for instance, shading or air intake. Due to the complexity of these elements, which consist of multiple assemblies, auxiliary systems were not included in the preliminary data collection. Instead, simplified 3D models of the auxiliary systems were developed to derive component volumes and were used to calculate the elements' specifications.

In case of a market available product, the Environmental Product Declaration (EPD) data is referenced and used as a basis for calculation. On the other hand, generic values of the materials are used in assessing the properties of the elements in research stage. Three exemplary auxiliary system were investigated in this study including two market available featuring a vertical roller blind shading system and a Photovoltaic-Thermal system, and two research project which features a solar thermal louver and a textile moss façade.

The vertical roller blind featured in this study is referenced to the product from IVRSA e.V. The system features a PVC + fiberglass textile with a motor and two guiding rails. In calculating the element's properties, the weight of the system was calculated and used as a normalized value to calculate for the system's carbon footprint. In reference to the EPD [1], the weight per square meter was considered as 9.16 kg/m<sup>2</sup> with a Global warming potential of 5.78 kgCO<sub>2</sub> eq/kg (53 kg CO<sub>2</sub> eq/m<sup>2</sup>).

Instead of directly multiplying the area to evaluate the system, an additional calculation step was taken, a 1 square meter equivalent model was generated as a simplified 3D model and calculated for weight. It is used as a benchmark to compare with the exact size used in the scenario. The weight of the two model were compared to derive a coefficient to be used in the value normalization. The assessment led to a coefficient of 1.45 when comparing a 1,000 x 1,000 mm system to the 1710 x 1223mm system used in this scheme. The coefficient is multiplied with the weight per square meter and GWP value to derive the weight and carbon footprint value of the design scheme. This allows for a relatively more precise result as the changes in dimension only incur higher material usage in the textile area not on the substructure, guiding rail or motor.

The solar thermal louver (Figure 3) represents the state-of-the-art intervention which incorporates solar cooling strategy as a part of the adaptive solar shading system. It protects the interior of the building through solar control, while utilizes the solar radiation in producing hot water. The design used in this scheme is referred to DESTINI [2], a research project which is a collaboration between PFE, Fraunhofer ISE, Borderstep Institut für Innovation und Nachhaltigkeit gemeinnützige GmbH, and Schindler Fenster + Fassaden GmbH [2].

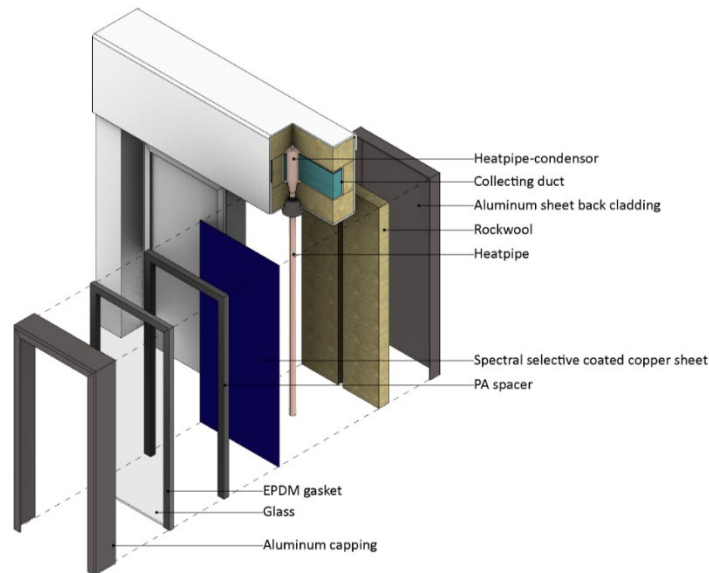


Figure 3 Exploded view of solar thermal louvre assembly (©Priedemann)

The properties of the auxiliary element were calculated from a simplified model taking into account only a major part of the system, excluding the specific connection elements and fasteners. The referenced values used in the calculation is summarized in Table 1.

Table 1 Material reference summary for Solar Thermal Louvre

Component	Density (kg/m <sup>3</sup> )	Reference	Carbon Footprint (kgCo2 eq)	Reference
Aluminum Component	2700	Multicare façade materials inventory	6.89	ICE DB V3.0, Aluminum extruded profile, European Mix, Inc Imports
Aluminum Connector	2700	Multicare façade materials inventory	6.83	ICE DB V3.0, Aluminum extruded profile, European Mix, Inc Imports
Aluminum Profile	2700	Multicare façade materials inventory	6.83	ICE DB V3.0, Aluminum extruded profile, European Mix, Inc Imports
Aluminum Sheet	2700	Multicare façade materials inventory	8.62	Façade Catalog from WP 11
Copper Absorber Sheet	8940	Multicare façade materials inventory	4.5	Façade Catalog from WP 11 *referred to copper sheet cladding
Copper Collecting Duct	8940	Multicare façade materials inventory	1.62	EPD: Copper Profile Elcowire AB   S-P-07032 [3]
Copper Heatpipe	8940	Multicare façade materials inventory	2.25	EPD: Copper tubes HME Copper Germany GmbH   EPD-Kiwa-EE-175069-en [4]

Glass	2500	Multicare façade materials inventory	1.44	Façade Catalog from WP 11 * refereed to single pane glass
Polyamide	1300	Multicare façade materials inventory	7.14	Insulating Profiles from PA66 GF25   Technoform Bautec Kunststoffprodukte GmbH   EPD-TIS-20.1 [5]
Rockwool	120	Multicare façade materials inventory	1.3	Façade Catalog from WP 11

The Photovoltaic-Thermal system features the market available product from Dualsun [6]. The GWP-total potential was referenced from the product's EPD [3]. The carbon footprint (kg CO<sub>2</sub> eq.) is considered at 1.71E+02 per square meter. The DSTF version of the product was considered with a weight of 36.3 kg per declared module (1.134 x 1.722m). Figure 4 shows the result of the assessment as simplified model of the photovoltaic-thermal system in the form of a Rhino3D block element.

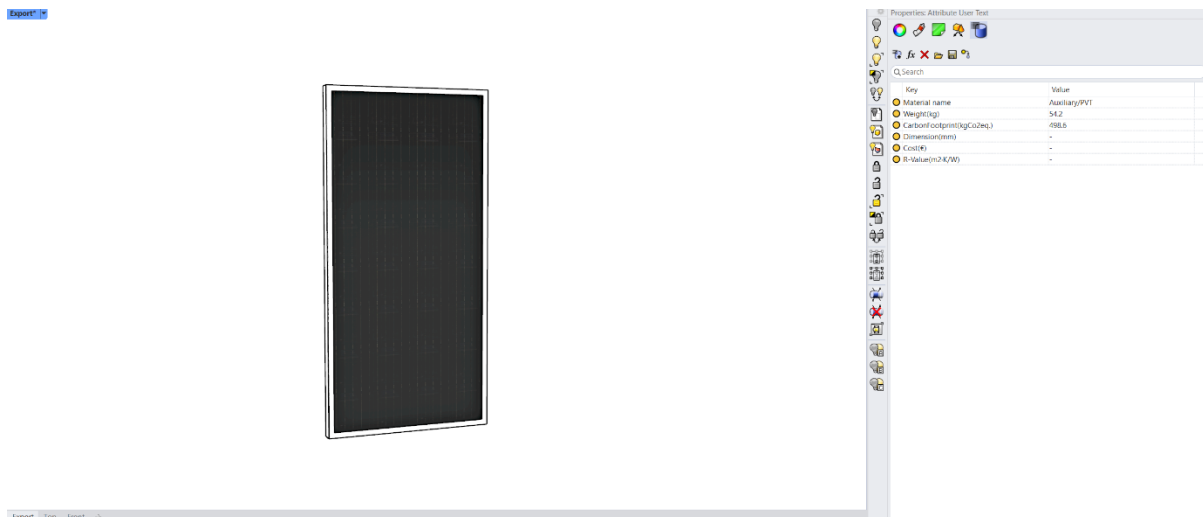


Figure 4 The Photovoltaic Thermal element as an auxiliary facade system embedded with the specification as an attribute user text on the right panel.

The textile moss façade (Figure 5) cladding was selected as an exemplary façade element which functions as an intervention that mitigates the environmental heat stress while providing social benefits. By utilizing textile as a substrate element, the auxiliary element is considered as a lightweight construction, therefore the insulation layers and structural system follows the optimized design for weight optimized scheme. The textile moss façade system in this scheme references research activities at PFE, for example the MossFact project [7] which is a collaboration between PFE, Gesellschaft zur Förderung von Medizin-, Bio- und Umwelttechnologien (GMBU) e.V. and M.Zellner GmbH. The project was funded by BMWK – Zentrales Innovationsprogramm Mittelstand (ZIM).

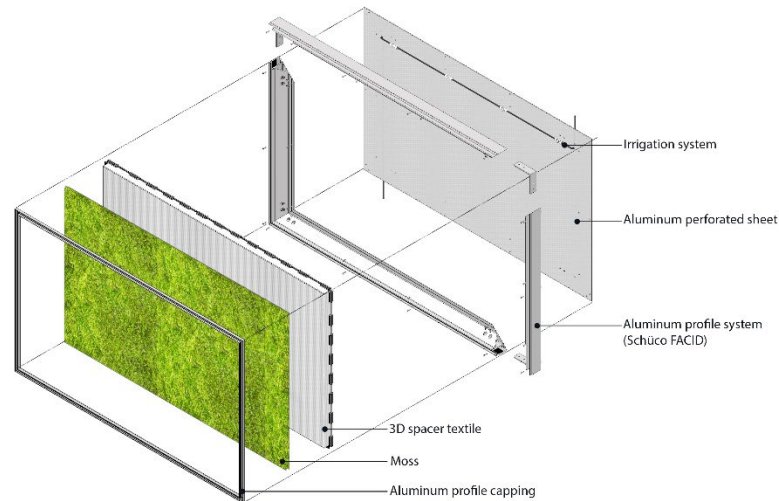


Figure 5 Textile Moss facade assembly (©Priedemann)

The properties of the auxiliary element were calculated from a simplified model where the irrigation system was not taken into consideration. The referenced values are summarized in Table 2.

Table 2 Material reference summary for Moss Textile Façade

Component	Density (kg/m <sup>3</sup> )	Reference	Carbon Footprint (kgCo <sub>2</sub> eq)	Reference
Aluminum Perforated Sheet*	2700	RV 5.0-8.0 (DIN24041).	8.62	Multicare façade materials inventory
Aluminum Profile	2700	-	6.83	ICE DB V3.0, Aluminum extruded profile, European Mix, Inc Imports
Moss	50	Kain et al., 2021 [8]	0	-
Textile**	80	Zellner ZAW 230301	11.6	EPD: Kvadrat A/S no: MD-23116-EN_rev1 [9]

\*The weight of the Aluminum Perforated Sheet is calculated with 35% opening. When considering the carbon footprint the whole panel is considered. It should be noted that the production process of perforation was not considered in this calculation.

\*\* The density of the textile is derived from the actual textile used in the project. Due to limited information and lacks EPD, the GWP value is referenced to a Polyester textile product.

## 2.2 Specification of Façade Geometrical Features

Building on the developments from WS5, the exoskeleton dimensions have been defined as 360 x 600 mm. In determining the façade implementation for this exoskeleton, two rear-ventilated façade system concepts were explored. Concept 1 as shown in Figure 6 explores the possibility of installing the substructure within the exoskeleton system, while the Concept 2 in Figure 7 investigates the possibility to position the façade system in front of the exoskeleton.

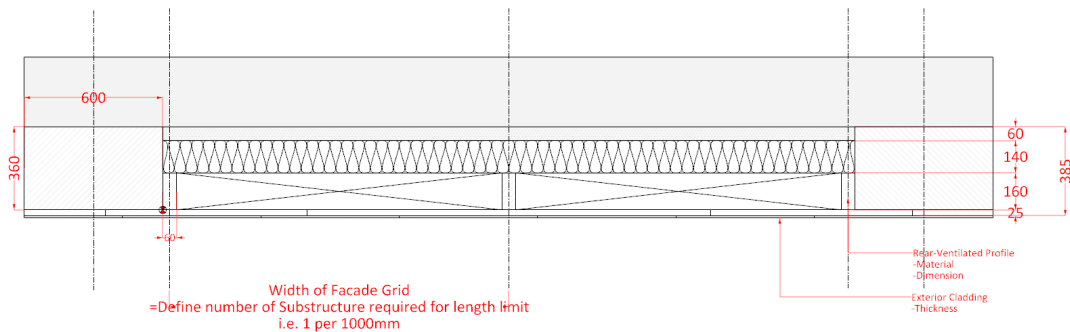


Figure 6: Rear Ventilated Façade system as Concept 1 with its substructure inside the exoskeleton system

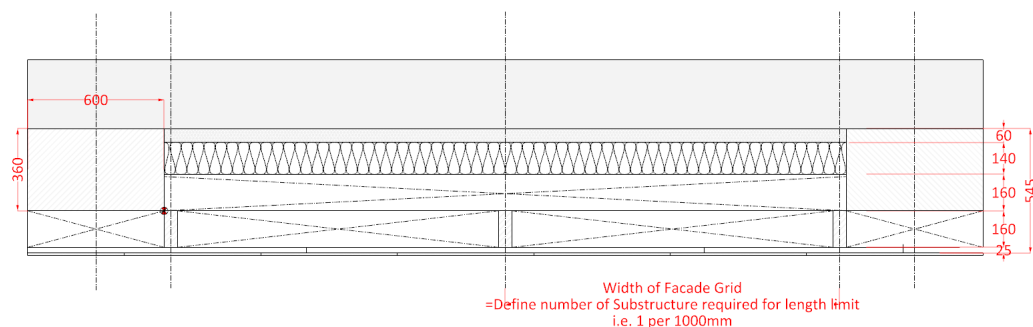


Figure 7: Rear Ventilated Façade System as Concept 2 with its substructure suspended in front of the exoskeleton system

Concept 1 with the substructure inside the exoskeleton was selected for further development as it has a relatively lower construction depth in comparison to concept 2. This minimizes material consumptions and the impact on daylight exposure in the interior.. In Concept 1, a rigid insulation with 60mm thickness is planned in front of the existing wall create a leveled surface plane. The main insulation layer is considered with 140mm thickness and is placed between the rigid insulation and the substructure. The substructure is planned as a 160mm in depth with 60mm in width. To reduce material usage, the area between the substructure remains open as a cavity area. The connection between the substructure and traverse profile is considered as a 25mm cavity. The construction built-up led to a total construction thickness of approximately 385mm.

Concept 1 is analyzed under various multi-criteria configurations to evaluate and compare different possible façade built-ups. Façades in general are complex systems of multiple layers, components and materials. Their performance is defined by the optimal and project specific composition within the assembly. This results in extensive design possibilities.

## Façade Configurator Tool

To facilitate the analysis, a parametric façade configurator tool as shown in Figure 8 was developed. The tool was developed in Grasshopper and Python under the Rhino 8 environment with a user interface from the Human UI plugin. The primary objective of the façade configurator is to enable a comparative assessment of the façade module based on various material combinations. It serves as a recommendation system to facilitate the planner as user to explore various design options.

The main functions of the Façade Configurator Tool can be summarized as follows:

- A. Determining the feasible positioning of the façade within the exoskeleton
- B. Generating façade cross-section profiles
- C. Creating a schematic 3D model of the façade assembly

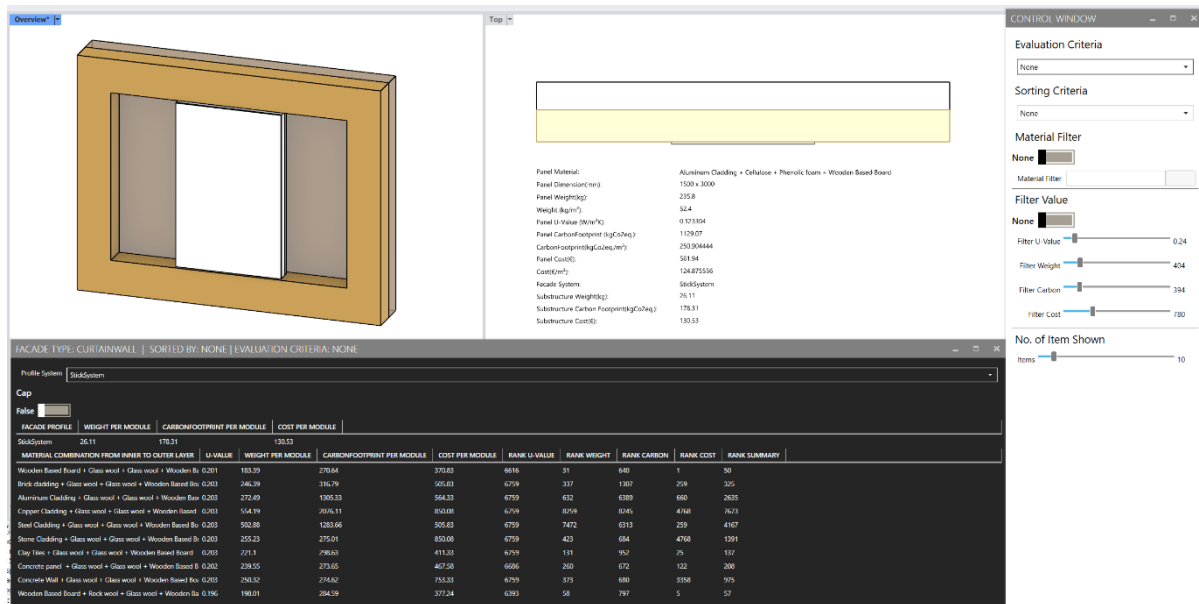


Figure 8 The interface of the Façade Configurator Tool consists of three main sections: the graphical representation of the façade in 3D and 2D (top left and top center), the result of the material combination assessment (bottom panel) and the control window which allows the user to sort and define filter parameters (right panel)

- A. Determining the feasible positioning of the façade within the exoskeleton

The Exoskeleton Generator is developed to facilitate the development of the façade design especially in the case of the demonstration site of Acerra and Bucharest. It provides the geometrical context for the planning of the façade dimensions and positions. The parametric feature of the definition allows the user to define the following specification:

- Primary wall thickness (mm)
- Exoskeleton Frame Width (mm)
- Exoskeleton Frame height (mm)
- Exoskeleton Column Cross section Height (mm)
- Exoskeleton Column Cross section Depth (mm)
- Exoskeleton Beam Cross section Height (mm)
- Exoskeleton Beam Cross section Depth (mm)

- B. Generating façade cross-section profiles

The façade configurator tool provides three main façade typologies including Rear Ventilated Façades, Curtain Walls and Composite Panels as examples for the assessment. They can be further categorized in six subcategories by profile cross sections and materials. The predefined profiles are embedded with properties such as material, density, carbon footprint, and cost for calculating the façade system properties. The façade system and information are summarized in Table 3. It should be noted that for the composite panel, the generator calculates the panel built-up based on the material inventory and therefore is not included as a part of the summary.

Table 3 Summary of Calculation parameter for facade profile

Façade System	Description
<p><b>Curtain Wall / Stick System</b>  Material: Aluminum  Density(kg/m<sup>3</sup>) : 2700  CarbonFootprint(kgCO<sub>2</sub>eq.) : 6.83*  Cost(Euro/kg): 5</p>	The stick system features a generic aluminum FWS-50 profile from Schüco. It can be configured with or without a capping component.
<p><b>Curtain Wall / Unitized System</b>  Material: Aluminum  Density(kg/m<sup>3</sup>) : 2700  CarbonFootprint(kgCO<sub>2</sub>eq.) : 6.83*  Cost(Euro/kg): 5</p>	The unitized system features the UDC 80 profile system from Schüco. It can be configured with or without a capping component.
<p><b>Curtain Wall /Wooden Profile</b>  Material: Hardwood  Density(kg/m<sup>3</sup>) : 530  CarbonFootprint(kgCO<sub>2</sub>eq.) : 0.306**  Cost(Euro/m): 7***</p>	The wooden profile includes a profile extension with an aluminum add-on profile from Schüco. It can be configured with or without a capping component.
<p><b>/Aluminum Add-on Profile</b>  Material: Aluminum  Density(kg/m<sup>3</sup>) : 2700  CarbonFootprint(kgCO<sub>2</sub>eq.) : 6.83*  Cost(Euro/kg): 5</p>	
<p><b>Rear Ventilated /Wooden Vertical Profile</b>  Material: Hardwood  Density(kg/m<sup>3</sup>) : 2700  CarbonFootprint(kgCO<sub>2</sub>eq.) : 0.306**  Cost(Euro/m): 7***</p>	The wooden profile is considered as a rectangular vertical wooden profile with aluminum traverse profile attached to it horizontally. The distribution of the traverse profile is based on the following calculation:
<p><b>/Traverse Profile</b>  Material: Aluminum  Density(kg/m<sup>3</sup>) : 2700  CarbonFootprint(kgCO<sub>2</sub>eq.) : 6.83*  Cost(Euro/kg): 5</p>	

**Rear Ventilated  
/Aluminum Vertical Profile**

Material: Aluminum  
 Density(kg/m<sup>3</sup>) : 2700  
 CarbonFootprint(kgCO<sub>2</sub>eq.) : 6.83\*  
 Cost(Euro/kg): 5

**/Traverse Profile**

Material: Aluminum  
 Density(kg/m<sup>3</sup>) : 2700  
 CarbonFootprint(kgCO<sub>2</sub>eq.) : 6.83\*  
 Cost(Euro/kg): 5

The aluminum profile is considered as a rectangular box profile with 3mm thickness with aluminum traverse profile attached to it horizontally.

\* ICE DB V3.0, Aluminum extruded profile, European Mix, Inc Imports

\*\*ICE DB V3.0, Timber,Hardwood – No Carbon Storage

\*\*\*Reference from Konsta solid structural timber [10]

The profile generation includes a parametric feature to define dimensions such like profile width and -height along with the inclusion of the capping system. As a first step, the user selects the façade profile system from the summary window (Figure 9).

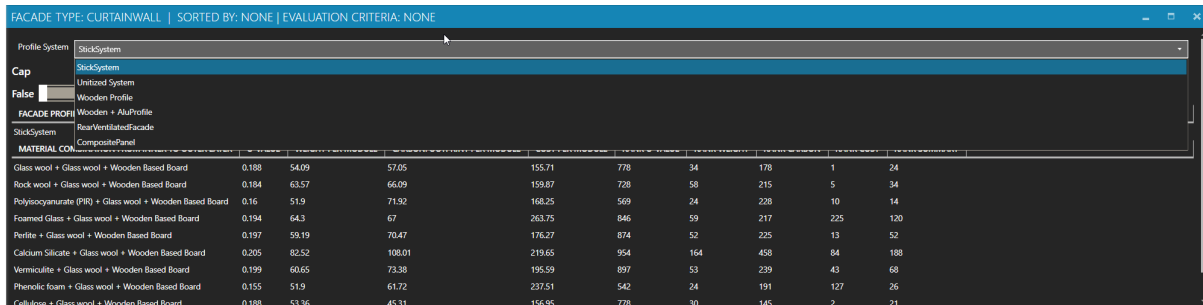


Figure 9 Selection of the facade system in the summary window

Once the profile system is selected, a surface model is created by the function. It displays the overall façade and profile dimension with additional properties. The dimension is further referenced for the subsequent façade module generation (Figure 10).

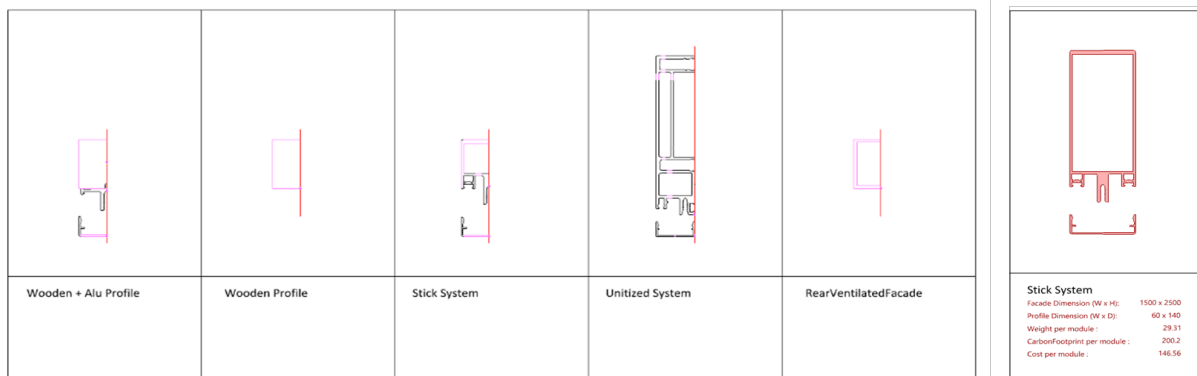


Figure 10 Facade Profile properties and calculation method

The façade profile properties calculated by the profile generator are listed in Table 4.

*Table 4 Façade Profile properties and calculation method*

Façade System Properties	Calculation Method
Weight per Module (kg)	Density * Profile Cross Section Area * Profile Perimeter
Carbon Footprint (kg CO <sub>2</sub> eq.)	System Weight * Carbon Footprint per kg
Cost per Module (Euro)	Curtain Wall System Weight * Cost per kg
	Rear Ventilated Façade System Weight * Cost per kg

### C. Creating a schematic 3D model of the façade assembly

The façade configurator tool is tailored to early-stage design decisions. Therefore, it generates schematic façade models which simplify the complex façade system into individual assembly layers. The layers taken into consideration are summarized in Table 5 for Curtain walls and Table 6 for rear ventilated facades.

*Table 5 Component layers considered in a curtain wall facade system generation*

Façade Layers: Curtain Wall	Description
Interior Cladding	It is considered as the cladding which encloses the infill panel from the back of the façade frame.
Wall Insulation	Wall insulation includes the additional insulation layer behind the interior cladding or main insulation layer and acts as an interface between the façade module and the primary wall.
Insulation	The insulation is positioned between the façade frame and/or the wall insulation.
Façade Structure	The façade structure of the curtain wall system takes into consideration both the mullion and transom profile. It is simplified as a rectangular frame structure based on the dimension defined by in the profile generator.
Exterior Cladding	The exterior cladding of the curtain wall system is positioned in front of the profiles towards the exterior side of the building.

Table 6 Component layers considered in a rear ventilated facade system generation

Façade Layers: Rear Ventilated Facade	Description
Wall Insulation	Wall insulation includes the additional insulation layer behind the main insulation layer and acts as an interface between the façade module and the primary wall.
Insulation	As a default situation, the insulation in a rear ventilated façade system is positioned behind the façade structure, but additional insulation between the façade structure could be included.
Façade Structure	<p>The façade structure of the rear ventilated façade takes into account the vertical profile on two side of the module.</p> <p>The traverse profile is positioned 200mm from the top and bottom edge, with a maximum array of &lt;800mm between each other. The no. of traverse profile is calculated according to the following method.</p> <p>No. of Traverse  <math>= (\text{Panel Height} - (2*200))/800</math></p> <p>The depth of the traverse profile is defined by the cavity thickness of the overall façade.</p>
Exterior Cladding	The exterior cladding of the rear ventilated façade is hanged onto the traverse profile and is positioned on the exterior side of the façade.

As parametric approach, the function enables the user to define the following properties and parameters to generate the schematic façade model.

- Façade Position – either between the exoskeleton or hanged in front of the exoskeleton
- Façade Width (mm)
- Façade Height (mm)
- Location of Façade (mm) – Distance from the primary wall
- Interior Cladding Thickness (mm)
- Wall Insulation Thickness (mm)
- Insulation Thickness (mm)
- Exterior Cladding Thickness (mm)
- Cavity Thickness (mm)

## 2.3 Evaluation and Rating of Material Combinations

### Design Options Assessment

The included Design Option Assessment function (Figure 11) performs an extensive calculation of design criteria per each material options of the façade component. The calculation ranks the calculated values and provides a summary. The resulting overview serves as a recommendation system which allows the users to quickly compare different façade configurations and to take decisions on the most suitable option depending on their design intents and resilience requirements.

The screenshot shows a software interface for 'Profile System' and 'StickSystem'. It displays a table with columns for 'MATERIAL COMBINATION FROM INNER TO OUTER LAYER', 'U-VALUE', 'WEIGHT PER MODULE', 'CARBONFOOTPRINT PER MODULE', 'COST PER MODULE', 'RANK U-VALUE', 'RANK WEIGHT', 'RANK CARBON', 'RANK COST', and 'RANK SUMMARY'. The table lists 16 different material combinations, such as 'Wooden Based Board + Glass wool + Glass wool + Wooden Based Board', and provides numerical values for each criterion. For example, the first combination has a U-value of 0.201, a weight of 157.17, a carbon footprint of 255.25, and a cost of 330.78.

Figure 11 Result of the Design Option Assessment Function.

The function utilizes the material inventory developed in Work package 11 as a reference for calculating the weight, U-value, carbon footprint and cost of the total façade configuration. In order to meet the fire protection requirements, insulation materials that fall under class C were removed from the inventory. In addition, the geometrical parameters were retrieved from the Profile generation and schematic Façade model generation function as geometrical references for thickness and area. The following calculations are based on the criteria per module which is then normalized into value per square meter at the end of the process. The assessment method for each criterion is summarized in Table 7.

Table 7 Calculation method to assess the performance parameters

Performance Parameter	Material Properties
<p><b>Weight (kg)</b>                      Weight = Density * Volume</p>	<p>Density (kg/m<sup>3</sup>)                      The mass per unit volume of a material which is used in calculated the component weight based on their volume.</p>
<p><b>U-Value (W/m<sup>2</sup>.K)</b>                      U-Value = 1/(Thickness of Material / Thermal Conductivity)</p>	<p>Thermal Conductivity (W/m·K)                      The ability of the material to conduct heat. It is also represented as λ value and is used in calculating the R-Value of the façade. In this assessment, the cavity thermal conductivity is omitted from the calculation.</p>

**Carbon Footprint (kgCO<sub>2</sub>eq.)**

Carbon Footprint = Carbon Footprint \*  
Weight

Carbon Footprint (kgCO<sub>2</sub>eq. / kg)

The carbon footprint is derived from the Global warming potential value of the materials based on EPD database

**Cost (Euros)**

Cost = Cost \* Area

Cost (Euros/sq.m)

The cost of the materials per square meter which is used in calculating the cost per component.

It should be remarked that for insulation layers, the cost result is generalized. It is based on cost per square meter and doesn't take into account the thickness of the material.

**Evaluation Criteria and Sorting Criteria**

The Design Option Assessment function incorporates the features to allow for additional valuation by giving weight to the ranking to provide additional insights by tailoring the result to specific optimization goal. The weighing process takes into account the priority of the criteria based on the analytics hierarchy process (AHP). With AHP, the parameters are given weight as percentage based on the defined selection criteria. The parameters are compared against each other to identify their hierarchical level to calculate the weighted coefficient. Four predefined settings have been defined depending on the objective of the evaluation:

- Performance driven solution  
U-value (0.47) / Carbon Footprint (0.28) / Weight (0.16) / Cost (0.09)
- Carbon footprint driven solution  
Carbon Footprint (0.47) / Weight (0.28) / U-value (0.16) / Cost (0.09)
- Weight-efficiency driven solution  
Weight (0.47) / U-value (0.28) / Carbon Footprint (0.16) / Cost (0.09)
- Cost-driven solution  
Cost (0.47) / U-value (0.27) / Weight (0.16) / Carbon Footprint (0.09)

The weighted coefficient is used in evaluating the materials ranking. The values in each material parameters are first normalized by value and average value. Then they are multiplied by the coefficient. The values of each parameter are added up to the summary rank. The function allows for sorting the ranking of the design options based on their Performance, Carbon Footprint, Weight, Cost and Summary Rank, or filter out the design options that fails to comply with defined thresholds.

## 2.4 Summary of Façade Systems for Performance Evaluation

### 1. Baseline: Hollow Brick Infill Wall

The as-built condition of the Acerra demonstrator building, comprising a reinforced concrete frame with masonry infill walls, formed the baseline scheme. The hollow clay brick masonry properties were derived from section drawings of the Acerra building, where specific materials and dimensions were documented. Since information on the window or glazing materials was not available in the documentation, a window with a U-value of 5.7 W/m<sup>2</sup>K was assumed, based on the Italian building code standards.

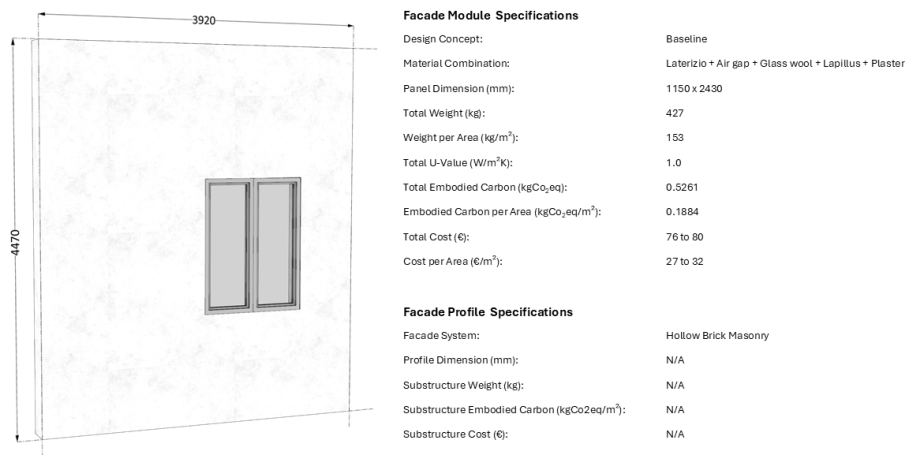


Figure 12 Input summary overview: Baseline: Hollow Brick Infill Wall

## 2. Benchmark: Rear-ventilated Cladding

The benchmark scheme represents the typical design approach commonly used when designing a rear-ventilated façade according to the current state of the art. Aluminum is selected as a main material for the overall construction and cladding elements. While PIR and Rock wool is utilized as insulation element for the wall and main insulation layers. The Aluminum cladding is specified as 3mm.

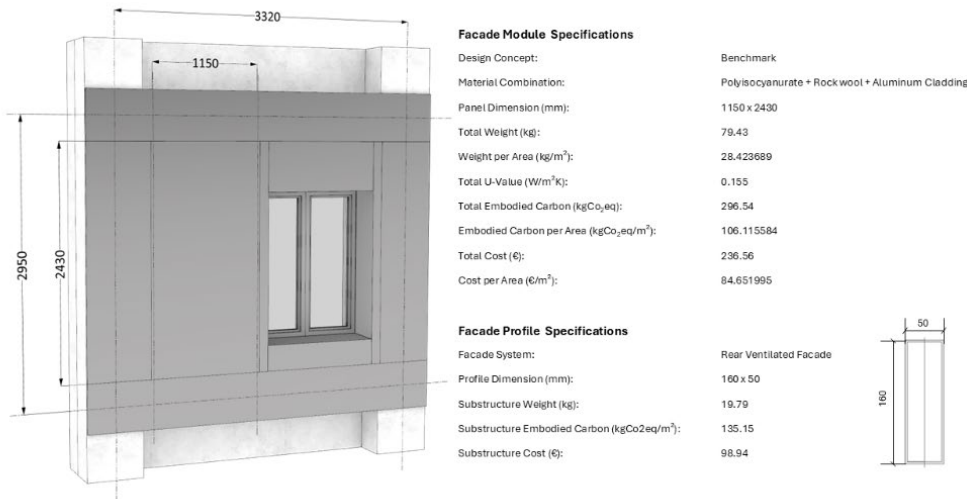


Figure 13 Input summary overview: Benchmark: Rear-ventilated Cladding

## 3. Rear-ventilated Cladding with Lightweight Materials

When sorting the design variations by materials with relatively light weight, the design configurator tool proposes a material combination of aluminum profile as the substructure for the rear-ventilated façade system. The insulation is a combination between the Phenolic foam board as a wall insulation and bio-based flax material as the main insulation. Due to a relatively low density in comparison with the other materials, a 10 mm wooden based board is considered as the exterior cladding.

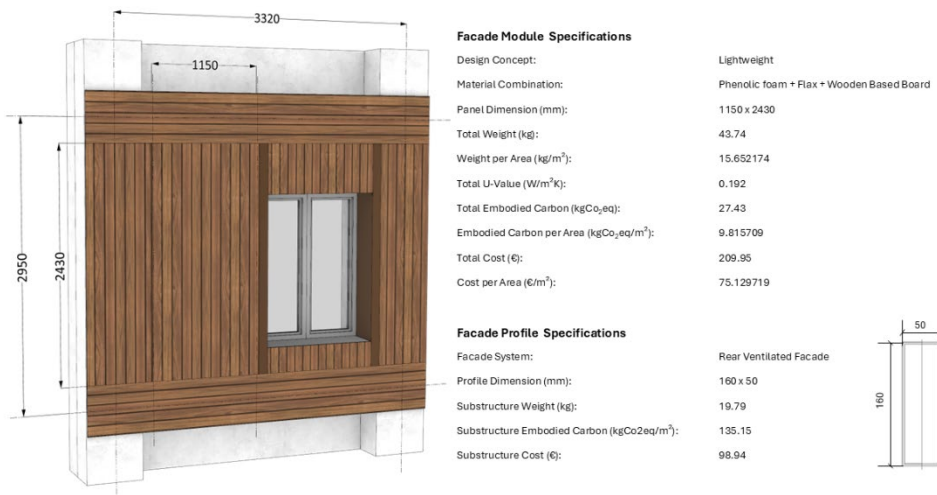


Figure 14 Input summary overview: Rear-ventilated Cladding with Lightweight Materials

#### 4. Rear-ventilated Cladding with Low Cost Materials

The recommendation from the façade configurator tool directed the design development of the cost-optimization scheme towards a wooden substructure with glass wool insulation in both the insulation layers. The cladding is also considered as a 10 mm wooden based board

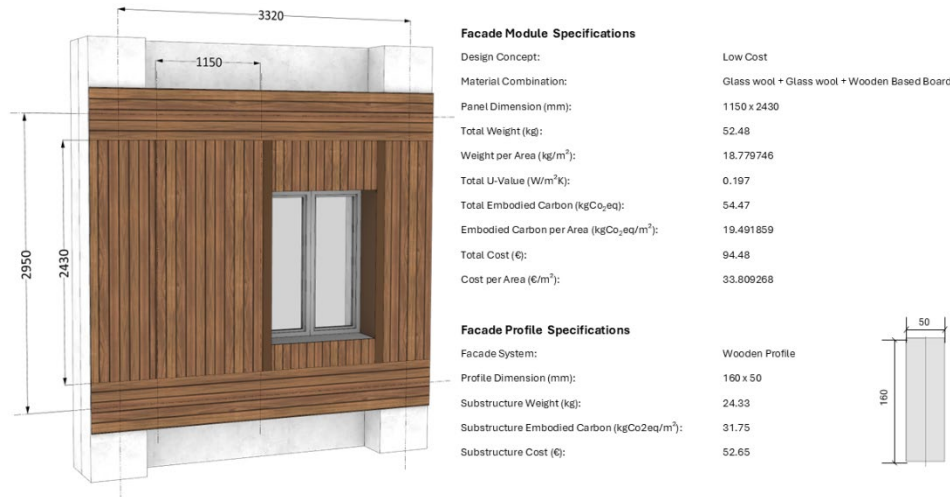


Figure 15 Input summary overview: Rear-ventilated Cladding with Low Cost Materials

#### 5. Rear-ventilated Cladding with Low Carbon Materials

The low carbon footprint façade scheme was developed based on the design recommendation of the façade configurator tool. The design approach is aimed towards bio-based materials; therefore, wooden profiles are utilized for the substructure. Cellulose present itself as insulation material with relatively low carbon and is utilized in both layers of insulation. The cladding is considered as a 10mm wooden based board.

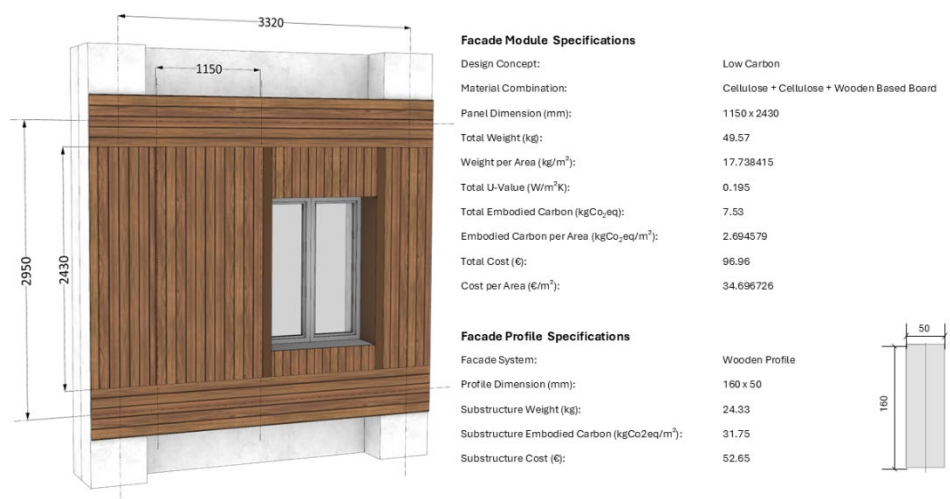


Figure 16 Rear-ventilated Cladding with Low Carbon Material

## 6. Auxiliary Element: Exterior Textile Shading

The exterior textile shading is a commonly used solar control system. It grants the control to the occupant to operate the blind according to the exterior conditions. The vertical roller blind product with the dimension of 1710 x 1223mm (Height x Width) is featured. The vertical operation incorporates a vertical movement motor and guiding rails.

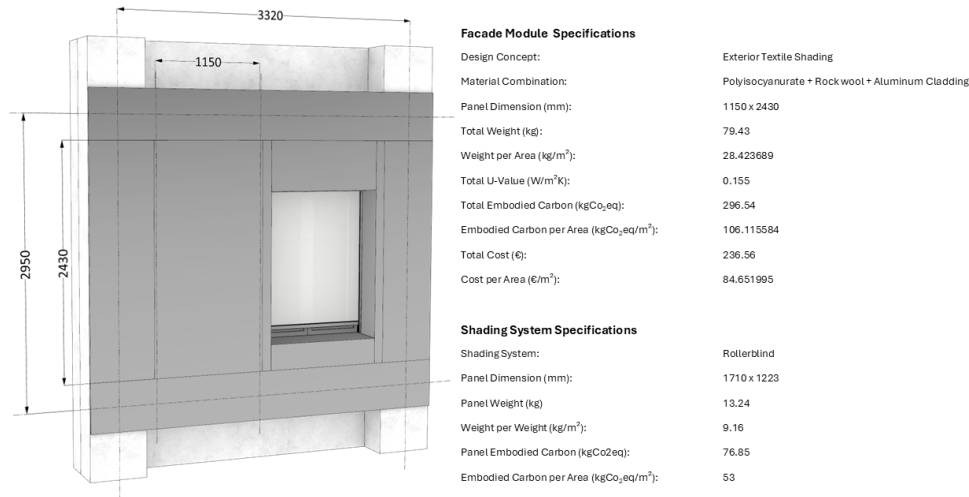


Figure 17 Input summary overview: Auxiliary Element: Exterior Textile Shading

## 7. Auxiliary Element: Solar Thermal Louver Shading System

The solar thermal louver used for this study consists of a copper absorber sheet which is connected to a heat pipe. The absorber sheet is coated with spectrally selective coating to maximize solar absorption. It is backed by 20mm Rockwool insulation for thermal efficiency and enclosed with an aluminum sheet. The design features a 15mm cavity, covered with a 3mm glass panel. It is designed as a closed system, where heat is transferred from the louver to the building through a dry connection mechanism. This design enables the louvers to rotate toward direct solar radiation without concerns about water connections.

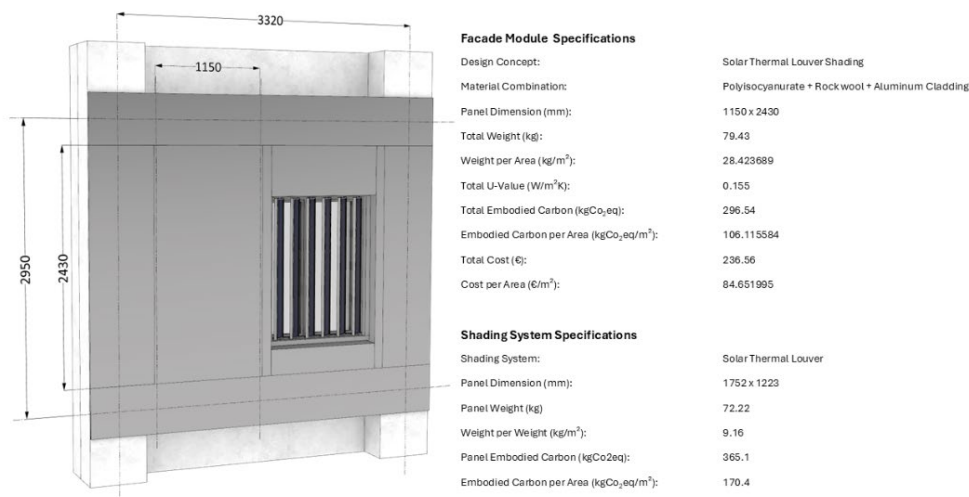


Figure 18 Input summary overview: Auxiliary Element: Solar Thermal Louver Shading System

### 8. Auxiliary Element: Moss Façade Cladding

The built-up of the moss façade used in this study is depicted in Figure 11. The moss is embedded onto a 5mm Spacer textile which is fixed on the Schüco FACID profile system. The element is enclosed with a 3mm perforated aluminum back panel.

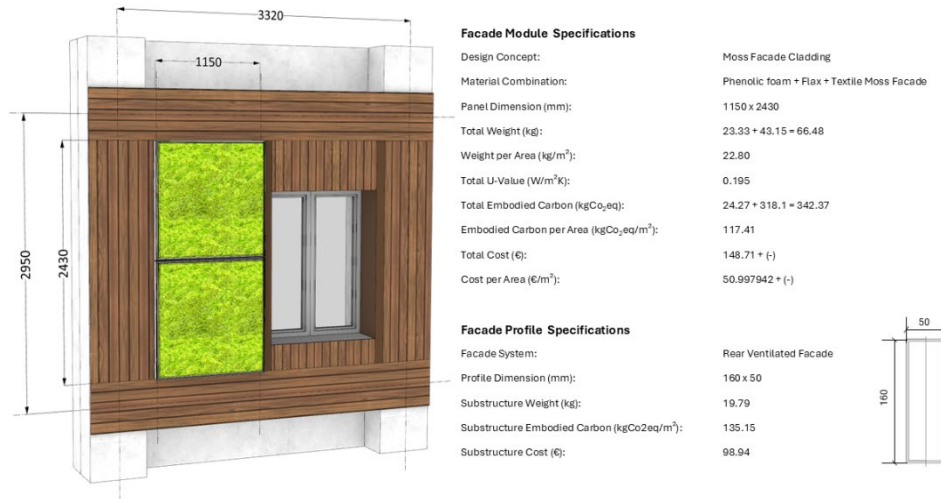


Figure 19 Input summary overview: Auxiliary Element: Moss Façade Cladding

### 9. Auxiliary Element: Photovoltaic Thermal (PVT)

The photovoltaic-thermal (PVT) element combines the electricity and hot water production in one module. The synergy utilizes water to cool down the PV, increasing its electrical efficiency as heat buildup is reduced [11]. The heat from the PV turns the cooling water to hot water which then can be used by the occupants of the building. This makes it a suitable auxiliary function for the residential building at Acerra.

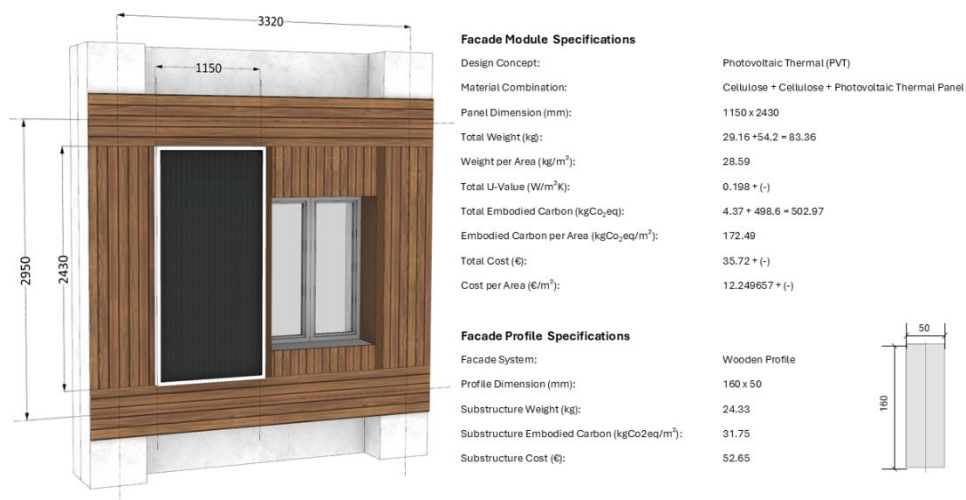


Figure 20 Input summary overview: Auxiliary Element: Photovoltaic Thermal (PVT)

### 3 Evaluation of Facade Systems

For the design cases defined from Section 2.4 performance evaluations were conducted across three domains: seismic resilience, heat resilience, and circularity. While some input parameters are shared across these domains, differences in modeling approaches and evaluation methods lead to slight variations in how the facade is analyzed in each case.

The building context required for evaluating facade performance varies depending on the domain. Seismic response varies by floor level due to variations in inter-storey drift. Heatwave response differs by floor, orientation (due to varying solar radiation), and room size (as thermal inertia affects temperature change rates). Since these building-related factors (e.g. ?) also influence the performance indicators used to compare facades, it was necessary to standardize the context for facade placement. A specific room with a 3 m<sup>2</sup> floor area, shown in Figure 12, was selected as the reference for analysis. This configuration was selected as a conservative approach, as it experiences the largest drift and receives maximum solar radiation.

The retrofit scenario considered in this evaluation retains the existing RC frame building with masonry infill walls, and new facade components are added. The baseline condition represents the as-built state, while eight alternative design options are assessed for comparison. These new configurations do not include window/glazing components. However, for heat resilience analysis, this exclusion means that direct solar radiation effects—a significant factor in thermal resilience—are not fully accounted for. To address this, calculations are based on a complete facade unit consisting of 10.74 m<sup>2</sup> opaque area and 2.73 m<sup>2</sup> glazing area (with a window-to-wall ratio of 0.25). This unit-based calculation applies to both seismic and heat resilience assessments. For circularity analysis, results are based on a facade module size of 2.8 m<sup>2</sup> (1.15 m width × 2.43 m height). While these differences in unit size do not affect the relative comparison of design options, they must be standardized when interpreting absolute values across domains.

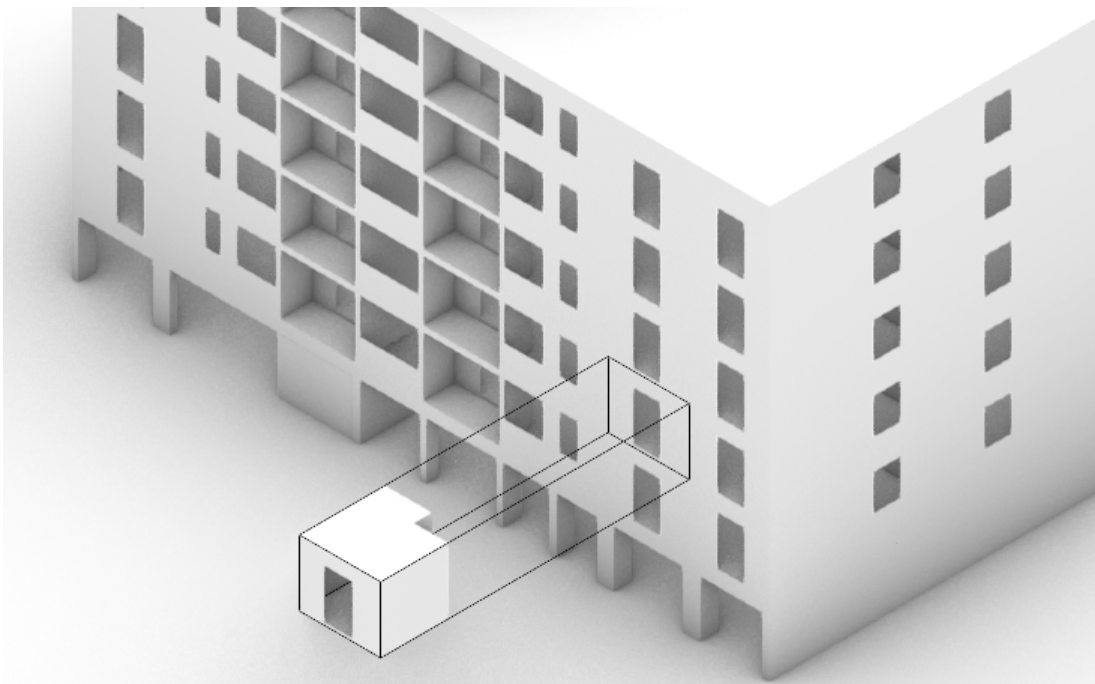


Figure 21 Facade unit in the building context, used for evaluation

### 3.1 Seismic Resilience

The seismic resilience indicators in this study are damage quantity (ft<sup>2</sup>) for the response stage and repair cost (USD) for the recovery stage. To evaluate these indicators, a response spectrum analysis (linear dynamic analysis) was conducted to obtain the engineering demand parameter (EDP), specifically the inter-story drift values. The structural model was developed and analyzed using OpenSees [12], with the Python package `openseespy` [13] facilitating the operations. The analysis involved constructing the structural model, performing modal analysis, and subsequently conducting response spectrum analysis to determine the drift values. These drift values were then used to assess damage and repair costs through Pelicun [14], another Python package that implements a stochastic damage and loss model based on the FEMA P-58 methodology [15].

Nine different design cases were considered, simplifying the seismic assessment into two structural configurations: a Reinforced Concrete (RC) frame building, which serves as the baseline, and an RC frame building combined with a low-damage timber-based exoskeleton. The baseline case, identified as ID: S\_F1, consists of an RC infilled frame (hollow brick masonry infills feature the facade system). Cases ID: S\_F2 to ID: S\_F9 incorporate an RC infilled frame system, along with an exoskeleton system consisting of an exterior wood stud wall. The Table 8 presents the configurations used for the seismic assessment.

*Table 8 Model configurations used for seismic assessment*

ID	Name	Structure	Façade - Opaque	Façade - Transparent
1	Baseline	RC frame	Masonry Infill	Masonry infills w/ window
2	Benchmark	RC frame + Exoskeleton	Masonry Infill + Wood Stud Wall	Masonry infills w/ window
3	Weight	RC frame + Exoskeleton	Masonry Infill + Wood Stud Wall	Masonry infills w/ window
4	Cost	RC frame + Exoskeleton	Masonry Infill + Wood Stud Wall	Masonry infills w/ window
5	Carbon	RC frame + Exoskeleton	Masonry Infill + Wood Stud Wall	Masonry infills w/ window
6	Rollerblind	RC frame + Exoskeleton	Masonry Infill + Wood Stud Wall	Masonry infills w/ window
7	Louver	RC frame + Exoskeleton	Masonry Infill + Wood Stud Wall	Masonry infills w/ window
8	Moss	RC frame + Exoskeleton	Masonry Infill + Wood Stud Wall	Masonry infills w/ window
9	PVT	RC frame + Exoskeleton	Masonry Infill + Wood Stud Wall	Masonry infills w/ window

#### 3.1.1 Structural Model Setup

##### *Structural Layout*

The RC frame building was simplified into a symmetric multi-bay configuration, consisting of nine longitudinal bays and five transverse. The structure has a total of six floors, each with a 3 m inter-storey height. The structural grid is presented in Figure 13.

The exoskeleton, a timber frame, was installed along the longitudinal side of the RC frame, with its columns aligned with the existing RC columns.

##### **Model - RC Frame**

The RC frame was modeled using `elasticBeamColumn` elements in OpenSees for both beams and columns. The section properties included a width of 300 mm, a height of 500

mm, and a Young's modulus of 25 GPa. To account for concrete cracking, the second moment of area was reduced by 50%.

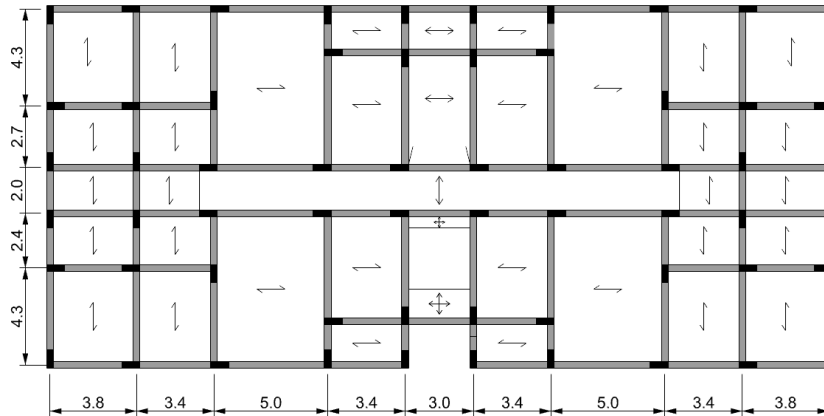


Figure 22 Structural grid of RC frame

### Model - RC Frame + Exoskeleton

Concerning the retrofitted configurations (i.e. SF\_2 to SF\_9), the exoskeleton's beams and columns were also modeled using elasticBeamColumn elements. The material properties were based on GL30C glued laminated timber, with a Young's modulus of 13 GPa, a shear modulus of 650 MPa, and cross-sectional dimensions of 600 mm in height and 320 mm in width. The exoskeleton was attached to the RC frame using rigid links, ensuring that the exoskeleton beam-column elements shared the same nodes as the RC frame along the outer longitudinal perimeter.

### Modal Analysis

For mass distribution, external nodes were assigned half the mass of adjacent beams, columns, floors, and infill walls, including the exoskeleton where applicable. Internal nodes accounted only for the mass of beams, columns, and floors. Material densities and applied loads were assigned as follows: the RC beams and columns had a density of 25 kN/m<sup>3</sup>, the load associated to infill walls is equal to 7 kN/m, and the floors had a load of 6 kN/m<sup>2</sup>, while the exoskeleton had a density of 4 kN/m<sup>3</sup>. A rigid diaphragm constraint was applied to ensure that nodes within each floor moved together.

Modal analysis was performed separately for the RC frame and the RC frame + Exoskeleton, with the results presented in Table 9, showing the vibration periods for each model.

Table 9 Vibration periods of RC Frame and RC Frame + Exoskeleton

Mode	RC Frame Period (s)	RC Frame + Exoskeleton Period (s)
1	1.077	1.039
2	1.004	0.863
3	0.790	0.657
4	0.360	0.345
5	0.334	0.285
6	0.258	0.214
7	0.217	0.206

### 3.1.2 Response Spectrum Analysis

#### Elastic Response Spectrum

The required elastic response spectrum for Acerra, corresponding to the Life-Safety Limit State ( $T_r = 475$  years), was utilized. Figure 14 illustrates the elastic response spectrum.

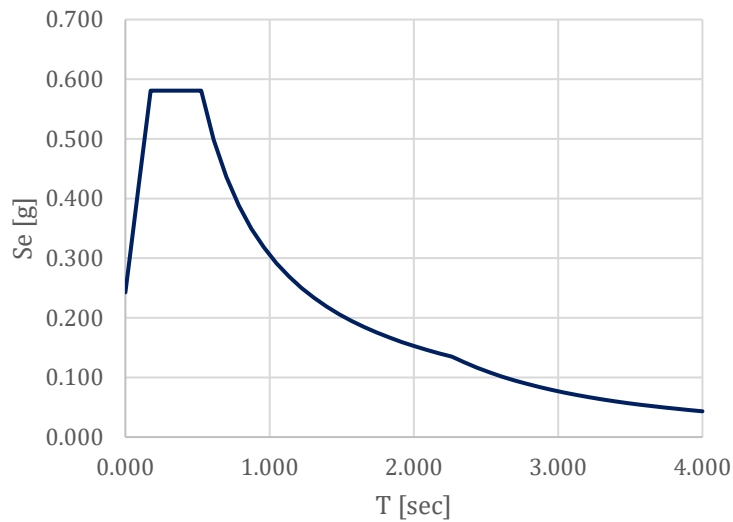


Figure 23 Life Safety Limit State Spectrum ( $T_r = 475$  years)

#### Drift obtained from Response Spectrum Analysis

Using the elastic spectrum, the responseSpectrumAnalysis function from OpenSees was employed to compute modal displacements. The Complete Quadratic Combination (CQC) method was then applied for modal combination to determine floor displacements and calculate inter-storey drift. Figure 15 presents the inter-storey drift results for two models: RC Frame and RC Frame + Exoskeleton.

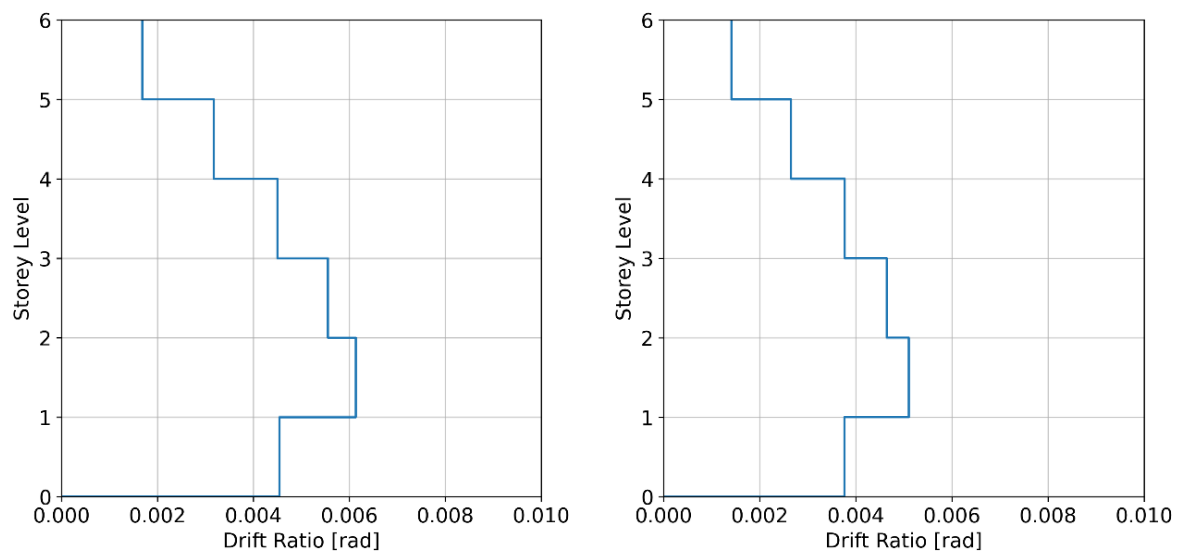


Figure 24 Drift Ratio for RC Frame (left), Drift ratio of RC Frame + Exoskeleton (right)

### 3.1.3 Calculation of Damage and Repair Cost

#### Damage Calculation

##### Fragility Curve - Masonry Infill, Masonry infills with window

The fragility specifications for masonry infill were sourced from Cardone and Perrone (2015), whose research consolidates results from previous experimental tests on RC frames with masonry infills and derives fragility curves accordingly.

##### Fragility Curve – Exterior wood stud wall

For wooden frame structures with panels, the fragility parameters were obtained from the FEMA P58 Fragility Database, specifically from B20.11.101, which describes exterior walls composed of light-framed wood with structural panel sheathing and gypsum wallboard without hold-downs.

Table 10 summarizes the description of each damage state along with the corresponding fragility parameters, including median and dispersion values. Using the demand values derived from the response spectrum analysis and the fragility input data, the mean quantity for each damage state was calculated through the Pelicun damage calculation function.

Table 10 Description of each damage state along with the corresponding fragility parameters

Fragility	Damage State	Damage Description	Median IDR (rad)	Dispersion
Masonry Infill	DS1	Detachment of infill, Light diagonal cracking	0.0015	0.5
	DS2	Extensive diagonal cracking	0.004	0.5
	DS3	Corner crushing and sliding of mortar joints	0.001	0.4
Masonry infills with window	DS1	Detachment of infill, Light diagonal cracking	0.001	0.5
	DS2	Extensive diagonal cracking	0.003	0.5
	DS3	Corner crushing and sliding of mortar joints	0.0075	0.4
Exterior wood stud wall	DS1	Slight separation of sheathing or nails which come loose	0.01	0.4
	DS2	Permanent rotation of sheathing, tear out of nails or sheathing	0.0175	0.4
	DS3	Fracture of studs, major sill plate cracking	0.025	0.4

#### Repair Cost Calculation

The parameters for the consequence model for masonry infill structures were obtained from Cardone and Perrone [16], while for wooden frame structures with panels, the parameters were sourced from the FEMA P58 Fragility Database [17]. To compute the repair cost, the consequence model was configured based on the relevant inputs. Table 11 provides a summary of the consequence inputs, where Theta 0 represents a function of the quantity of damage, indicating the average repair cost for lower and upper quantity values. The repair cost is expressed in USD, with the unit of quantity measured in 100 SF (100 ft<sup>2</sup>). Theta 1 denotes the dispersion value. By configuring the loss model in Pelicun, the repair cost was calculated.

Table 11 Summary of the consequence inputs

Consequence model	Damage State	Repair Measures	Theta 0	Theta 1
Masonry Infill	DS1	Cosmetic repair and patch some cracks	3112,4979 5,20	0.22
	DS2	Patch some cracks	7053,9958 5,20	0.44
	DS3	Demolish existing wall and construct new wall. Re-install existing frame (if any)	33400,47299 5,20	0.44
Masonry infills with window	DS1	Cosmetic repair and patch some cracks	672,1075 5,20	0.22
	DS2	Patch some cracks	1298,1836 5,20	0.44
	DS3	Demolish existing wall and construct new wall. Re-install existing frame (if any)	4925,6984 5,20	0.44
Exterior Wood stud wall	DS1	Remove exterior pliable siding, replace loose nails, reinstall siding.	2990,1840 3,8	0.256634
	DS2	Remove exterior pliable siding, remove wood sheathing, install new sheathing, reinstall siding.	3300,2337.5 3,8	0.369072
	DS3	Remove and replace siding, sheathing, studs and plates. Provide shoring as required.	5400,3825 3,8	0.109784

Table 12 summarizes the calculation results for all nine design cases. The damage quantities for opaque and transparent areas were computed separately for each damage state and then aggregated to determine the total damage quantity. Similarly, the repair costs were calculated individually for opaque and transparent areas before being summed to obtain the total repair cost.

Table 12 Seismic calculation results for all nine design cases

ID	Name	Opaque				Transparent				Total			
		Damage DS1 (ft2)	Damage DS2 (ft2)	Damage DS 3 (ft2)	Repair Cost (USD)	Damage DS1 (ft2)	Damage DS2 (ft2)	Damage DS 3 (ft2)	Repair Cost (USD)	Damage DS1 (ft2)	Damage DS2 (ft2)	Damage DS 3 (ft2)	Repair Cost (USD)
1	Baseline	19.3	37.4	17.6	9124	6.0	18.2	15.0	1014	25.3	55.6	32.6	10138
2	Benchmark	9.0	1.6	0.6	352	8.4	19.7	10.8	7092	42.2	58.2	22.5	7444
3	Weight	9.0	1.6	0.6	352	8.4	19.7	10.8	7092	42.2	58.2	22.5	7444
4	Cost	9.0	1.6	0.6	352	8.4	19.7	10.8	7092	42.2	58.2	22.5	7444
5	Carbon	9.0	1.6	0.6	352	8.4	19.7	10.8	7092	42.2	58.2	22.5	7444
6	Rollerblind	9.0	1.6	0.6	352	8.4	19.7	10.8	7092	42.2	58.2	22.5	7444
7	Louver	9.0	1.6	0.6	352	8.4	19.7	10.8	7092	42.2	58.2	22.5	7444
8	Mossfacade	9.0	1.6	0.6	352	8.4	19.7	10.8	7092	42.2	58.2	22.5	7444
9	PVT	9.0	1.6	0.6	352	8.4	19.7	10.8	7092	42.2	58.2	22.5	7444

### 3.2 Heat Resilience

The heat resilience indicators used for assessment include cumulative unmet standard effective temperature hours (SETH (degree-hours)) for the response stage and recovery time (hours) for the recovery stage. These indicators were calculated by means of dynamic thermal simulations conducted during a heatwave period. Honeybee [18], a Grasshopper plugin, was used to create the model, which was then translated into an OpenStudio model [19] and subsequently converted into an IDF file for simulation in EnergyPlus [20]. From the EnergyPlus SQL output file, hourly indoor air temperature and relative humidity data were extracted to evaluate the Standard Effective Temperature (SET) at each timestep. The cumulative unmet SETH was calculated by summing the degree-hours exceeding the critical SET threshold, while recovery time was determined by measuring the total hours required for the SET to return below the critical threshold.

The nine design cases primarily differ in terms of material properties, specifically the composition of material layers. Table 13 summarizes the input configurations for each energy model. As the building envelope materials influence heat transfer, additional opaque wall layers (cases H\_F2 to H\_59) were added to the baseline opaque wall on the exterior side, forming a single construction wall. For transparent walls, a simple glazing window was uniformly applied across all design cases.

In H\_F6, a dynamic exterior roller blind was implemented, operating based on a predefined setpoint. In H\_F7, a thermal louver was modeled as an additional aperture component attached to the window, with specific width, depth, and angle.

*Table 13 Configuration of models for heat resilience assessment*

ID	Name of facade case	Opaque (material layers from interior to exterior) component	Transparent component
H_F1	Baseline	Plaster + Laterizio + Air gap + Glass wool + Lapillus + Plaster	Simple Glazing Window
H_F2	Benchmark	<b>Baseline Opaque</b> + Polyisocyanurate (PIR) + Rock wool + Aluminum Cladding	Simple Glazing Window
H_F3	Weight	<b>Baseline Opaque</b> + Phenolic foam + Flax + Wooden Based Board	Simple Glazing Window
H_F4	Cost	<b>Baseline Opaque</b> + Glass wool + Glass wool + Wooden Based Board	Simple Glazing Window
H_F5	Carbon	<b>Baseline Opaque</b> + Cellulose + Cellulose + Wooden Based Board	Simple Glazing Window
H_F6	Rollerblind Shading	<b>Baseline Opaque</b> + Polyisocyanurate (PIR) + Rock wool + Aluminum Cladding	Simple Glazing Window + <b>Rollerblind</b>
H_F7	Thermal Louver	<b>Baseline Opaque</b> + Polyisocyanurate (PIR) + Rock wool + Aluminum Cladding	Simple Glazing Window + <b>Louver</b>

H_F8	Mossfacade	<b>Baseline Opaque +</b> Phenolic foam + Flax + Textile Moss Facade	Simple Glazing Window
H_F9	PVT	<b>Baseline Opaque +</b> Cellulose + Cellulose + Photovoltaic Thermal Panel	Simple Glazing Window

### 3.2.1 Energy Model Setup

#### Material Properties

Table 14 outlines the material properties used in the design cases, including thermal transmittance (U-value) and the solar heat gain coefficient (SHGC). The hollow clay brick masonry properties were derived from section drawings of the Acerra building, as the specific materials and dimensions were available. A Honeybee opaque construction was created to accurately represent the as-built condition. Since information on the window or glazing material was not available in the documentation, the Italian building code standard for windows with a U-value of 5.7 W/m<sup>2</sup>K was used. A simple glazing window from the Honeybee construction set, which complies with this standard, was selected as an input. For the rear-ventilated wall, applicable to design cases H\_F2 to H\_F9, its thermal transmittance was modeled using a Honeybee opaque material with no mass and added as an additional surface layer to the existing hollow brick masonry wall.

The roller blind was modeled with a slat width of 100 mm and a slat angle of 60 degrees. The louver was designed with a depth of 300 mm, consisting of four vertical fins tilted at a 45-degree angle, placed in front of the glazing section of the window.

Table 14 Material properties used in design cases

ID	Material Layers	U Value	SHGC
H_F1 ~ F_F9	Plaster + Laterizio + Air gap + Glass wool + Lapillus + Plaster	1.000	-
H_F2	Polyisocyanurate (PIR) + Rock wool + Aluminum Cladding	0.155	-
H_F3	Phenolic foam + Flax + Wooden Based Board	0.192	-
H_F4	Glass wool + Glass wool + Wooden Based Board	0.197	-
H_F5	Cellulose + Cellulose + Wooden Based Board	0.195	-
H_F6	Polyisocyanurate (PIR) + Rock wool + Aluminum Cladding	0.155	-
H_F7	Polyisocyanurate (PIR) + Rock wool + Aluminum Cladding	0.155	-
H_F8	Phenolic foam + Flax + Textile Moss Facade	0.195	-
H_F2	Cellulose + Cellulose + Photovoltaic Thermal Panel	0.198	-
H_F1 ~ F_F9	Simple Glazing Window	4.72	0.25

#### Building Program and Operation

The Midrise Apartment program from the Honeybee database was used, providing preset values for occupancy at 0.025 people per square meter, lighting at 8.8 W/m<sup>2</sup>, electric equipment load at 6.0 W/m<sup>2</sup>, and a ventilation rate of 0.31 air changes per hour (ACH). The building was modeled as unconditioned, indicating the absence of an HVAC system. Instead, natural ventilation was facilitated through an operable window, programmed to open when the indoor temperature reached at least 20°C, provided that the outdoor temperature was not below 15°C. If the outdoor temperature fell below this threshold, the window remained closed.

The dynamic exterior roller blind was set to activate when solar radiation incident on the window exceeded  $350 \text{ W/m}^2$ .

### 3.2.2 Thermal Dynamic Analysis

#### *Heatwave Weather File*

Daily climate observations from the Capodichino Airport weather station for the period 1951–2023 were obtained from the Open-Meteo database [21]. To identify the historical heatwave year for simulation, the CTX90pct criterion was applied. This criterion defines a heatwave as a period when the maximum daily temperature exceeds the 90th percentile for at least three consecutive days. Using the Hotspell Python package [22], the CTX90pct criterion was applied to the daily climate observations, and the heatwave period from August 8–15, 2021, was identified as having the highest maximum daily temperature ( $36.9^\circ\text{C}$ ). Historical weather data at an hourly timestep was then acquired from the NCDC database [23] and converted into the EnergyPlus Weather File (EPW) format for use in the simulation

#### *Running EnergyPlus*

For each design case, an Input Data File (IDF) was created, incorporating the material configurations, building program, and operational parameters. Using the IDF file and the EPW weather file, an EnergyPlus simulation was conducted. The simulation generated an SQL results file, which contains hourly data on indoor air temperature and relative humidity for analysis.

### 3.2.3 Calculation of unmet SETH and Recovery Time

For the calculation of Standard Effective Temperature (SET), only the indoor air temperature and relative humidity from the hourly simulation results were used. Other parameters required for SET calculation were kept as default, including an airspeed of  $0.1 \text{ m/s}$  and a metabolic rate of  $1.1$ , corresponding to a seated person. The processed hourly SET data was then segmented into two periods: the heatwave period (timestep 5256–5447) and the post-heatwave period (timestep 5447–8760). The critical SET threshold was set at  $30^\circ\text{C}$  (SET30), which is adopted as a passive survivability threshold from LEED pilot credits [24].

To calculate unmet SETH, the total hours where SET exceeded  $30^\circ\text{C}$  during the heatwave period were counted. The SET degree exceeding this threshold was multiplied by the number of hours, resulting in a degree-hour value. For recovery time, the first timestep when SET dropped below  $30^\circ\text{C}$  after the heatwave was identified, and the difference between this timestep and the end of the heatwave period was used to determine recovery time.

Table 15 summarizes the heat resilience calculation results for all nine design cases. The baseline case had an opaque wall U-value of  $1 \text{ W/m}^2\text{K}$ , whereas other design cases had values close to  $0.15 \text{ W/m}^2\text{K}$ , a nearly tenfold reduction. This significant difference in thermal transmittance primarily influenced the variation in unmet SETH values. For S\_F7, the external roller blind, and S\_58, the external louver, both design strategies contributed to a

50% reduction in solar radiation compared to cases with only a window and no shading measures.

In terms of recovery time, all design cases exhibited a similar value of 25 hours, indicating that within a day, as the outdoor temperature dropped, the SET returned below 30°C. However, this suggests that either the threshold definition or the methodology for measuring recovery time may require refinement to better capture variations between different design cases.

Table 15 Heat resilience calculation results for nine design cases

ID	Name	Heat Response Unmet SETH (Degree Hour)	Heat Recovery Recovery Time (Hour)
S_F1	Baseline	311.81	25.00
S_F2	Benchmark	288.61	25.00
S_F3	Weight	289.28	25.00
S_F4	Cost	289.37	25.00
S_F5	Carbon	289.33	25.00
S_F6	Rollerblind	267.11	25.00
S_F7	Thermal Louver	259.40	25.00
S_F8	Mossfacade	289.33	25.00
S_F9	PVT	289.38	25.00

### 3.3 Circularity

The end-of-life (EOL) emissions quantify the impacts of decommissioning each building element. It takes into account standard market practices (discarding, recovering, recycling or reusing). The Grasshopper plugin Bombyx 2 [25] was utilized to estimate EOL emissions for each building element, measured in kgCO<sub>2</sub>eq. Subsequently, this data was used to calculate total emissions for each of the façade configurations.

The input data required to perform this assessment is the material and weight of each element, both which could be extracted from the baked geometry of the façade configurations. The correspondence between user-defined materials and those available in the Bombyx database was done manually, as detailed in Table 16.

Table 16 Correspondence between the user-defined materials and those available in the Bombyx database.

Material	Bombyx correspondence
Glass wool	10.001.03: Glass wool(100 kg/m <sup>3</sup> )
Rock wool	10.008.01: Rock wool, Flumroc(32 kg/m <sup>3</sup> )
Polyisocyanurate (PIR)	10.006.01: Polyurethane, Swisspor PIR
Phenolic foam	10.003: Phenolic resin (PF)
Cellulose	10.010: Cellulose fibers(35 kg/m <sup>3</sup> )
Flax	10.016: Flax fibers
Wooden Based Board	07.004: Hardboard
Brick cladding	02.001: Brick

Aluminum Cladding	06.002: Aluminum profile, bright
Plaster	04.001: Plaster / white plaster
Cement	01.001: Lean concrete (without reinforcement)

After manually setting up the correspondence between the materials, the EOL emissions calculation was done automatically by Bombyx, requiring both the weight and type of material as input data. The calculations for each of the 8 modules, as well as for the baseline wall (existing), can be seen in Table 17.

*Table 17 End-of-life (EOL) emissions for the 8 modules, as well as the baseline (existing) wall.*

Alternative	Material	Weight (kg)	Bombyx EOL (kgCO <sub>2</sub> eq/kg)	Per material (kgCO <sub>2</sub> eq)	Total (kgCO <sub>2</sub> eq)
Baseline Wall (Existing) Only	Plaster	186.46	0.013	2.42	69.76
	Brick	3580.05	0.013	46.54	
	Glass Wool	23.31	0.06	1.40	
	Cement	1491.69	0.013	19.39	
Benchmark	PIR	7.00	2.65	18.55	91.50
	Rock Wool	48.99	0.06	2.94	
	Aluminum Cladding	23.44	0.008	0.19	
	Aluminum	8.03	0.008	0.06	
Weight	Baseline Wall			69.76	96.18
	Phenolic foam	7.00	3.09	21.63	
	Flax	16.33	0.235	3.84	
	Wooden Based Board	20.41	0.044	0.90	
	Aluminum	8.03	0.008	0.06	
Cost	Baseline Wall			69.76	73.03
	Glass Wool	9.62	0.06	0.58	
	Glass Wool	22.45	0.06	1.35	
	Wooden Based Board	20.41	0.044	0.90	
	Hardwood	10.30	0.044	0.45	
Carbon	Baseline Wall			69.76	73.21
	Cellulose	8.75	0.072	0.63	
	Cellulose	20.41	0.072	1.47	
	Wooden Based Board	20.41	0.044	0.90	
	Hardwood	10.30	0.044	0.45	
Rollerblind	Cellulose			69.76	91.50
	PIR	7.00	2.65	18.55	
	Rock Wool	48.99	0.06	2.94	
	Aluminum Cladding	23.44	0.008	0.19	
	Aluminum	8.03	0.008	0.06	
Solar Louver	Baseline Wall			69.76	91.50
	PIR	7.00	2.65	18.55	
	Rock Wool	48.99	0.06	2.94	
	Aluminum Cladding	23.44	0.008	0.19	

	Aluminum	8.03	0.008	0.06	
	Baseline Wall			69.76	
Mossfacade	Phenolic foam	7.00	3.09	21.63	95.29
	Flax	16.33	0.235	3.84	
	Aluminum	8.03	0.008	0.06	
	Baseline Wall			69.76	
PVT	Cellulose	8.75	0.072	0.63	72.31
	Cellulose	20.41	0.072	1.47	
	Hardwood	10.30	0.044	0.45	
	Baseline Wall			69.76	

### *Limitations and future improvements*

Bombyx 2 uses the Swiss LCA database, therefore making it more representative of Switzerland's context. To verify its applicability to other countries, particularly the Netherlands, its data was cross-referenced with the OneClickLCA dataset. It should be noted that all the calculations performed were limited to the substructures of the eight façade configurations and the existing wall.

Possible future improvements could focus on integrating the Bombyx workflow within a fully parametric environment and removing the manual correspondence between materials. Such changes could improve the framework's versatility and scalability, while reducing user's errors.

## 4 Catalogue of Pre-evaluated Systems

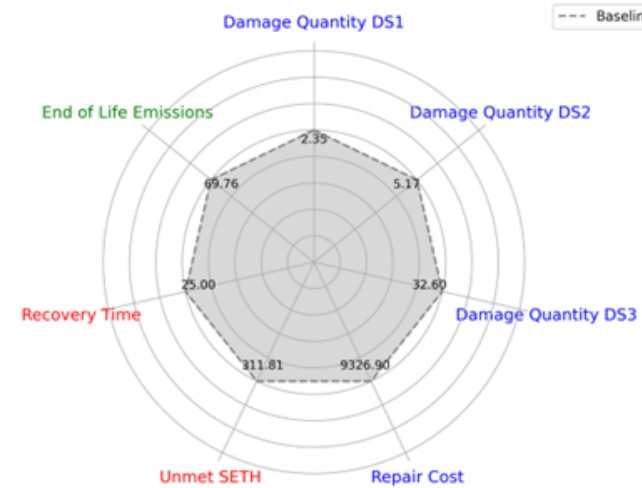
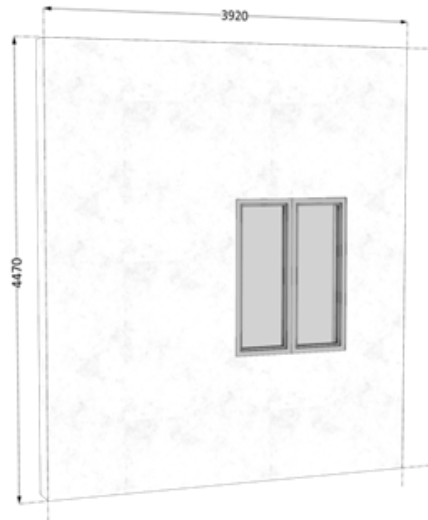
Table 18 presents the calculation results for seismic resilience, heat resilience, and circularity across nine design cases.

- **Seismic Resilience** Adding an exoskeleton to the baseline design reduced repair costs and overall damage. In particular, severe damage (damage state 3) was largely reduced, while minor damage (damage states 1 and 2) increased slightly. This increase in minor damage is expected since adding additional components increases the total damageable elements. However, the results indicate that the exoskeleton greatly mitigated overall damage severity by largely reducing the most critical damage state.
- **Heat Resilience** Adding components to the baseline design reduced unmet SETH values, primarily due to additional insulating layers that improved thermal transmittance by a factor of ten. Among different strategies, reducing solar radiation transmittance proved to be the most effective approach. This is evident from the lowest unmet SETH values recorded in shading-focused designs, such as ID6 (roller blind) and ID7 (solar louver).
- **Circularity** Introducing additional components to the baseline increased emissions, as end-of-life (EOL) emissions are calculated based on material weight (i.e., new components contribute additional weight). Among all design cases, ID3 exhibited the highest EOL emissions. Although this case incorporated phenolic foam to achieve a lightweight construction, phenolic foam has a high kgCO<sub>2</sub>eq/kg value, greatly contributing to overall emissions.

Table 18 Calculation results for seismic resilience, heat resilience, and circularity across nine design cases.

	Seismic Resilience Damage Quantity DS1 (m2)	Seismic Resilience Damage Quantity DS2 (m2)	Seismic Resilience Damage Quantity DS3 (m2)	Seismic Resilience Repair Cost (EUR)	Heat Resilience Unmet SETH (Degree Hour)	Heat Resilience Recovery Time (Hour)	Circularity End of Life (kgCO <sub>2</sub> eq)
1 Baseline	2.35	5.17	32.60	9326.90	311.81	25.00	69.76
2 Benchmark	3.92	5.41	2.09	6848.28	288.61	25.00	91.50
3 Weight	3.92	5.41	2.09	6848.28	289.28	25.00	96.18
4 Cost	3.92	5.41	2.09	6848.28	289.37	25.00	73.03
5 Carbon	3.92	5.41	2.09	6848.28	289.33	25.00	73.21
6 Rollerblind	3.92	5.41	2.09	6848.28	267.11	25.00	91.50
7 Louver	3.92	5.41	2.09	6848.28	259.40	25.00	91.50
8 Moss	3.92	5.41	2.09	6848.28	289.33	25.00	95.29
PVT	3.92	5.41	2.09	6848.28	289.38	25.00	72.31

## 1. Baseline: Hollow Brick Infill Wall



### System Description

Facade Type	Hollow Brick Infill Wall
Construction Type	Masonry Infill
Material Layers	Laterizio + Air gap + Glass wool + Lapillus
Facade Surface Area	2.8 m <sup>2</sup>

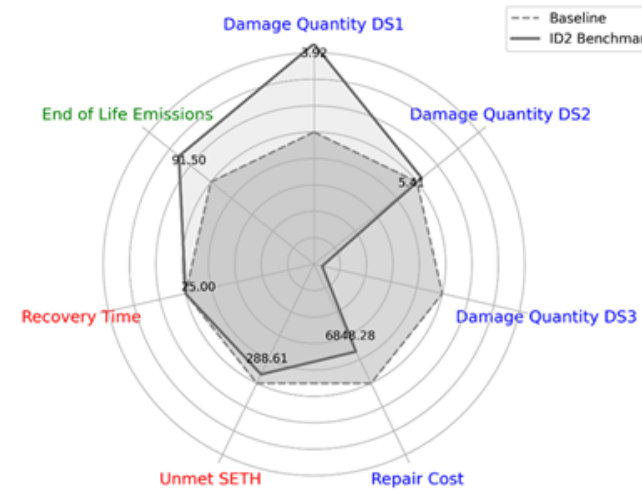
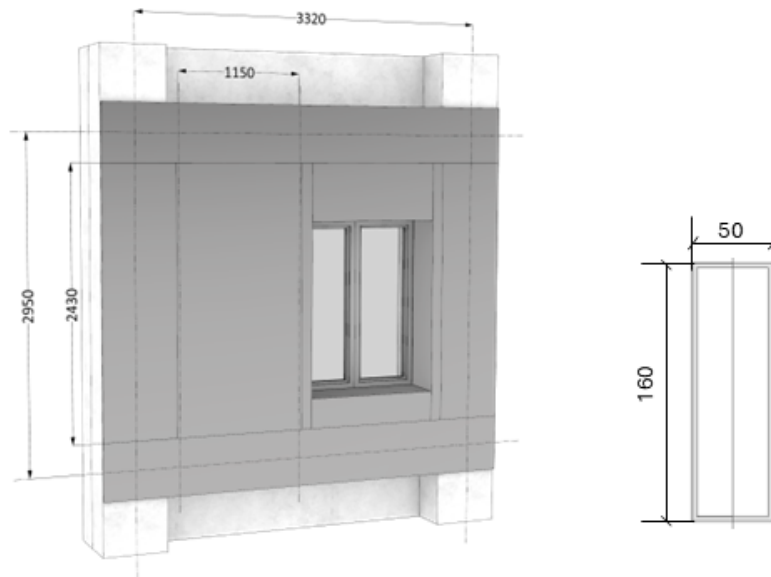
### System Performance

Unit Weight	427	kg
Unit Cost	80	€
Unit Embodied Carbon	0.5261	kgCO <sub>2</sub> eq
Unit U-Value	1.0	W/m <sup>2</sup> K

### Resilience & Circularity Score

Seismic Damage	2.35	m <sup>2</sup>
Seismic Repair Cost	9326	€
Heatwave Unmet SET	311	°C·h
Heatwave Recovery Time	25	h
End of Life Emissions	69	kgCO <sub>2</sub> eq

## 2. Benchmark: Rear-ventilated Cladding



### System Description

Facade Type	Rear Ventilated
Construction Type	Masonry Infill + Wood Stud Wall
Material Layers	Polyisocyanurate + Rockwool + Aluminum
Facade Surface Area	2.8 m <sup>2</sup>

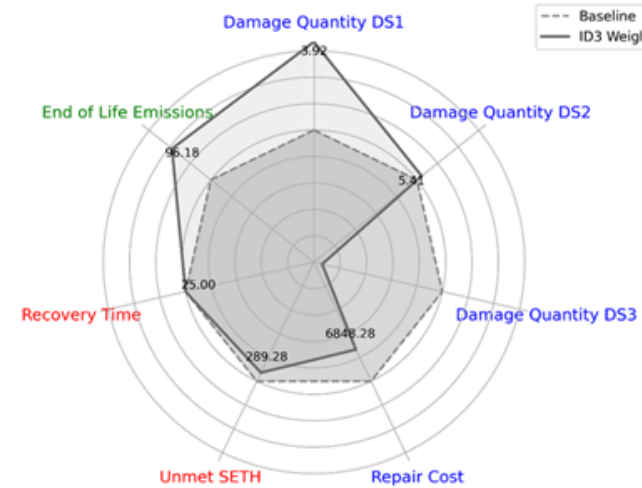
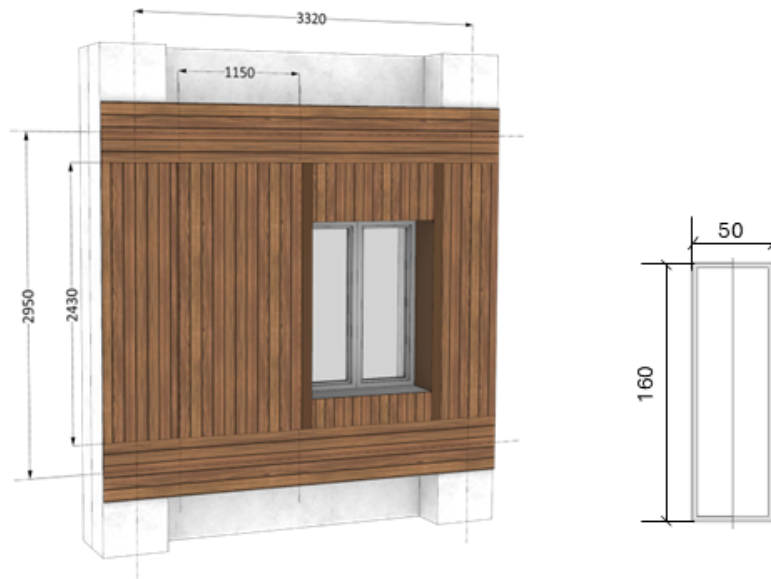
### System Performance

Unit Weight	79.43 kg
Unit Cost	236.56 €
Unit Embodied Carbon	296.54 kgCO <sub>2</sub> eq
Unit U-Value	0.155 W/m <sup>2</sup> K

### Resilience & Circularity Score

Seismic Damage	3.92	m <sup>2</sup>
Seismic Repair Cost	6848	€
Heatwave Unmet SET	288	°C·h
Heatwave Recovery Time	25	h
End of Life Emissions	91	kgCO <sub>2</sub> eq

### 3. Rear-ventilated Cladding with Lightweight Materials



#### System Description

Facade Type	Rear Ventilated
Construction Type	Masonry Infill + Wood Stud Wall
Material Layers	Phenolic foam + Flax + Wooden Board
Facade Surface Area	2.8 m <sup>2</sup>

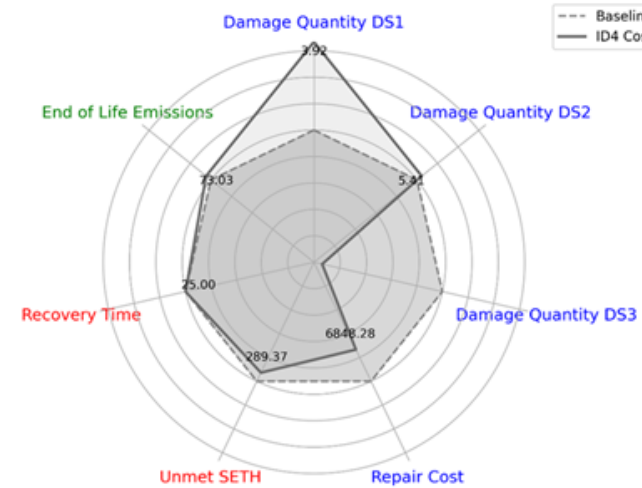
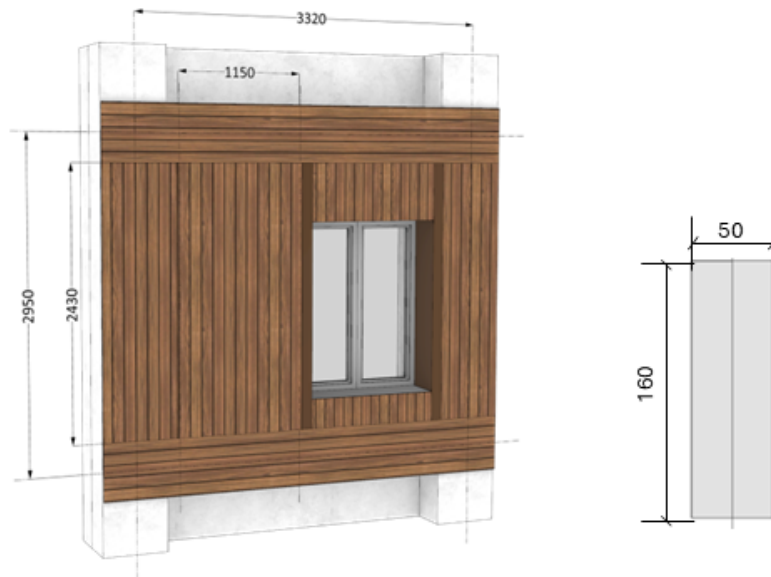
#### System Performance

Unit Weight	43.74 kg
Unit Cost	209.95 €
Unit Embodied Carbon	27.43 kgCO <sub>2</sub> eq
Unit U-Value	0.192 W/m <sup>2</sup> K

#### Resilience & Circularity Score

Seismic Damage	3.92	m <sup>2</sup>
Seismic Repair Cost	6848	€
Heatwave Unmet SET	289	°C·h
Heatwave Recovery Time	25	h
End of Life Emissions	96	kgCO <sub>2</sub> eq

## 4. Rear-ventilated Cladding with Low Cost Materials



### System Description

Facade Type	Wooden Profile
Construction Type	Masonry Infill + Wood Stud Wall
Material Layers	Glass wool + Glass wool + Wooden Board
Facade Surface Area	2.8 m <sup>2</sup>

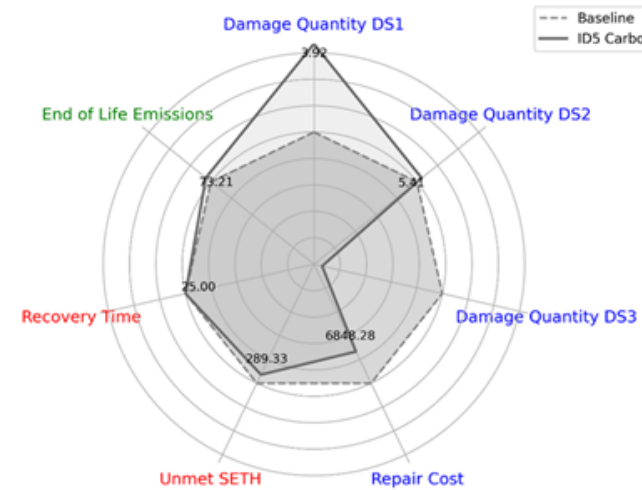
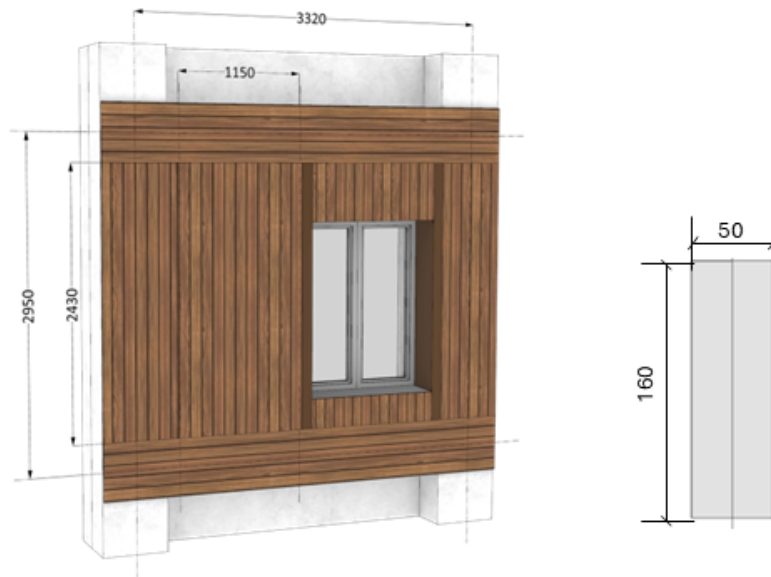
### System Performance

Unit Weight	52.48 kg
Unit Cost	94.48 €
Unit Embodied Carbon	54.47 kgCO <sub>2</sub> eq
Unit U-Value	0.197 W/m <sup>2</sup> K

### Resilience & Circularity Score

Seismic Damage	3.92	m <sup>2</sup>
Seismic Repair Cost	6848	€
Heatwave Unmet SET	289	°C·h
Heatwave Recovery Time	25	h
End of Life Emissions	73	kgCO <sub>2</sub> eq

## 5. Rear-ventilated Cladding with Low Carbon Materials



### System Description

Facade Type	Wooden Profile
Construction Type	Masonry Infill + Wood Stud Wall
Material Layers	Cellulose + Cellulose + Wooden Board
Facade Surface Area	2.8 m <sup>2</sup>

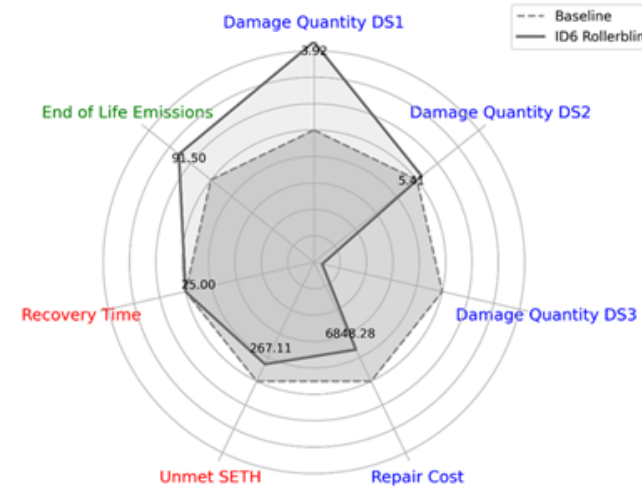
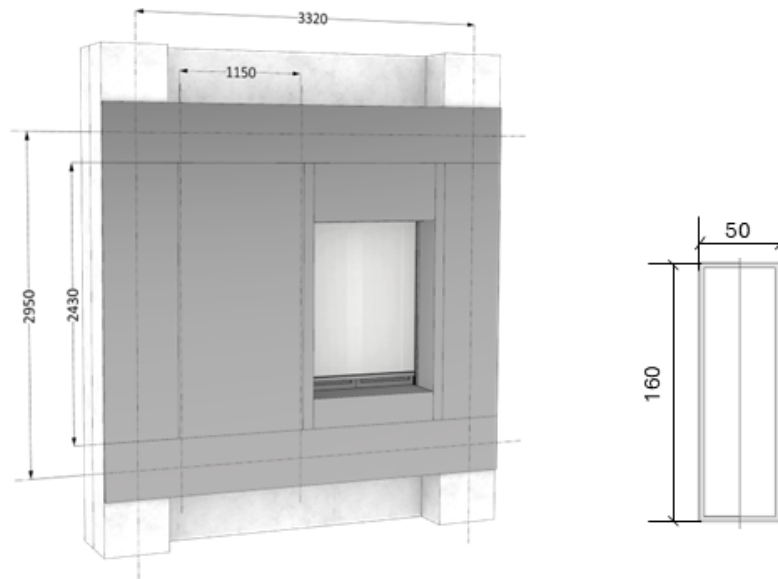
### System Performance

Unit Weight	49.57 kg
Unit Cost	96.96 €
Unit Embodied Carbon	7.53 kgCO <sub>2</sub> eq
Unit U-Value	0.195 W/m <sup>2</sup> K

### Resilience & Circularity Score

Seismic Damage	3.92	m <sup>2</sup>
Seismic Repair Cost	6848	€
Heatwave Unmet SET	289	°C·h
Heatwave Recovery Time	25	h
End of Life Emissions	73	kgCO <sub>2</sub> eq

## 6. Auxiliary Element: Exterior Textile Shading



### System Description

Facade Type	Rear Ventilated
Construction Type	Masonry Infill + Wood Stud Wall
Material Layers	Polyisocyanurate + Rockwool + Aluminum
Facade Surface Area	2.8 m <sup>2</sup>

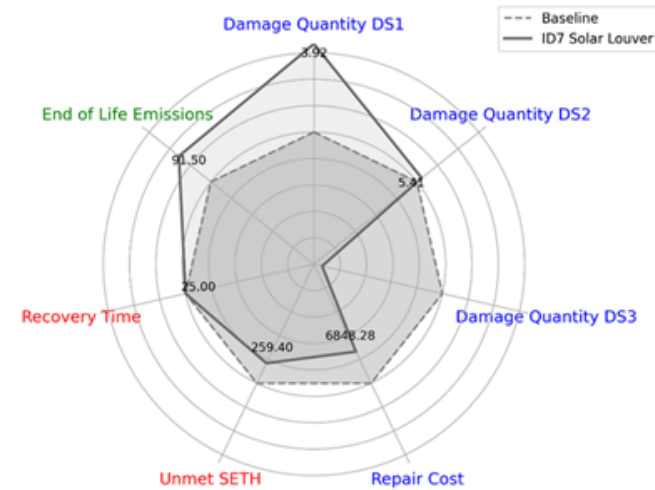
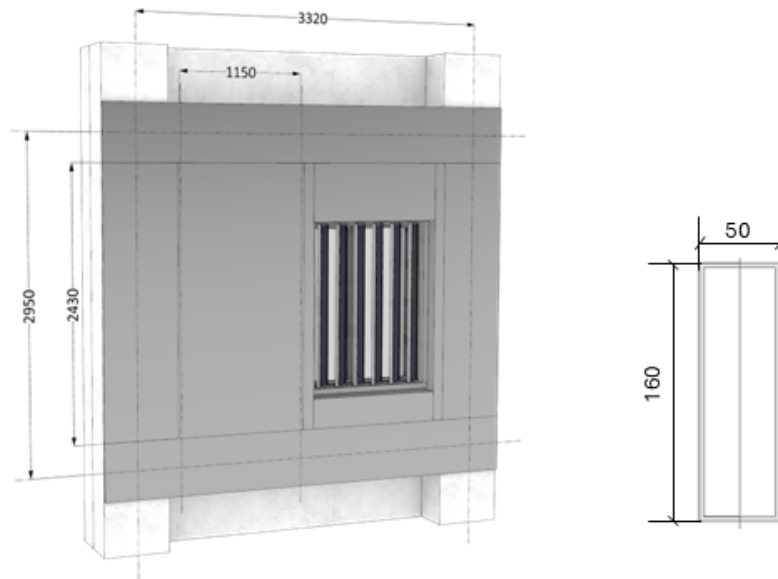
### System Performance (Auxiliary)

Unit Weight	13.24 kg
Unit Cost	N/A €
Unit Embodied Carbon	76.85 kgCO <sub>2</sub> eq
Unit U-Value	N/A W/m <sup>2</sup> K

### Resilience & Circularity Score

Seismic Damage	3.92 m <sup>2</sup>
Seismic Repair Cost	6848 €
Heatwave Unmet SET	267 °C·h
Heatwave Recovery Time	25 h
End of Life Emissions	91 kgCO <sub>2</sub> eq

## 7. Auxiliary Element: Solar Thermal Louver Shading System



### System Description

Facade Type	Rear Ventilated
Construction Type	Masonry Infill + Wood Stud Wall
Material Layers	Polyisocyanurate + Rockwool + Aluminum
Facade Surface Area	2.8 m <sup>2</sup>

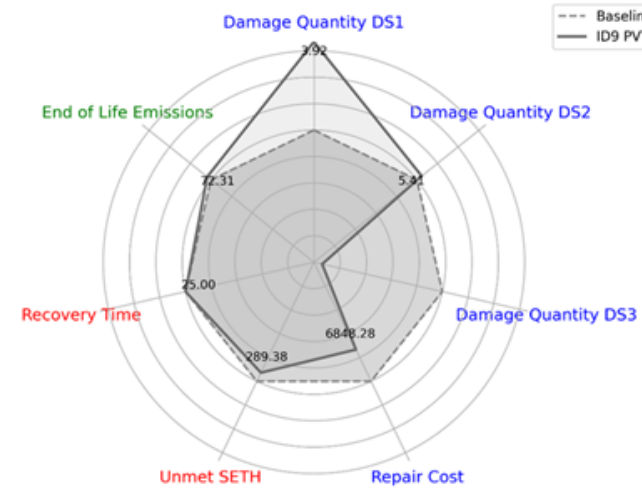
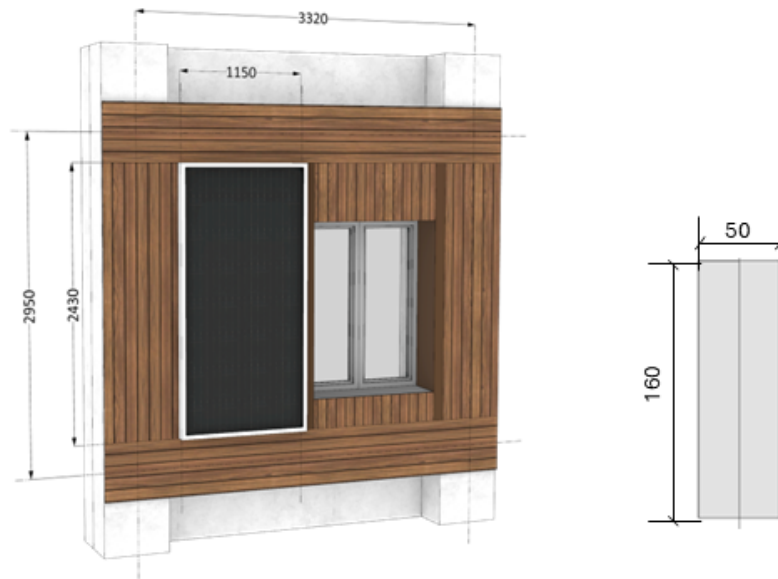
### System Performance (Auxiliary)

Unit Weight	72.22	kg
Unit Cost	N/A	€
Unit Embodied Carbon	365.1	kgCO <sub>2</sub> eq
Unit U-Value	N/A	W/m <sup>2</sup> K

### Resilience & Circularity Score

Seismic Damage	3.92	m <sup>2</sup>
Seismic Repair Cost	6848	€
Heatwave Unmet SET	259	°C·h
Heatwave Recovery Time	25	h
End of Life Emissions	91	kgCO <sub>2</sub> eq

## 9. Auxiliary Element: Photovoltaic Thermal (PVT)



### System Description

Facade Type	Wooden Profile
Construction Type	Masonry Infill + Wood Stud Wall
Material Layers	Cellulose + Cellulose + PVT Panel
Facade Surface Area	2.8 m <sup>2</sup>

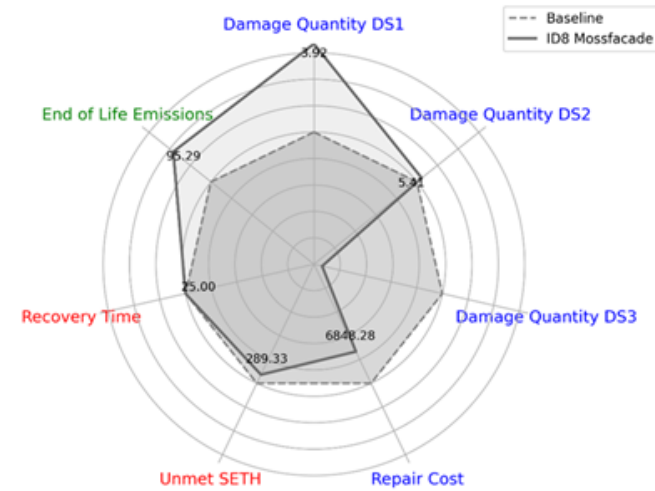
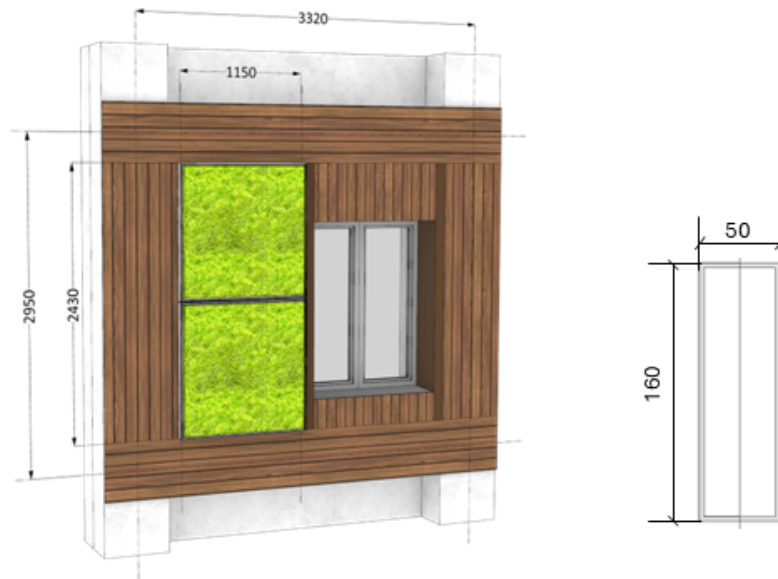
### System Performance

Unit Weight	83.36 kg
Unit Cost	35.72 €
Unit Embodied Carbon	502.97 kgCO <sub>2</sub> eq
Unit U-Value	0.198 W/m <sup>2</sup> K

### Resilience & Circularity Score

Seismic Damage	3.92	m <sup>2</sup>
Seismic Repair Cost	6848	€
Heatwave Unmet SET	289	°C·h
Heatwave Recovery Time	25	h
End of Life Emissions	72	kgCO <sub>2</sub> eq

## 8. Auxiliary Element: Moss Façade Cladding



### System Description

Facade Type	Rear Ventilated
Construction Type	Masonry Infill + Wood Stud Wall
Material Layers	Phenolic foam + Flax + Wooden Board
Facade Surface Area	2.8 m <sup>2</sup>

### System Performance

Unit Weight	66.48 kg
Unit Cost	148.71 €
Unit Embodied Carbon	342.37 kgCO <sub>2</sub> eq
Unit U-Value	0.195 W/m <sup>2</sup> K

### Resilience & Circularity Score

Seismic Damage	3.92	m <sup>2</sup>
Seismic Repair Cost	6848	€
Heatwave Unmet SET	289	°C·h
Heatwave Recovery Time	25	h
End of Life Emissions	95	kgCO <sub>2</sub> eq

## 5 Conclusion

The evaluation of façade systems was conducted by considering various design concepts for retrofitting a six-story residential building constructed in the 1980s in Acerra, Italy. The as-built condition, consisting of an RC frame with a masonry infill wall, was considered the baseline case. This methodology was designed as a guiding procedure for retrofit design decisions, which is why the baseline condition was included in all design cases. From this, a benchmark case was established by adding an Exoskeleton to the RC frame and a rear-ventilated cladding system to the exoskeleton frame. Building upon the benchmark case, additional design variations were developed by modifying materials and components to achieve specific objectives, such as low-carbon, low-cost, or lightweight solutions. Furthermore, auxiliary elements such as shading devices, moss, or PVT cladding were integrated to enhance climate performance. In total, nine design cases were defined.

These nine design cases were assessed across three key domains: seismic resilience, heat resilience, and circularity. Key performance indicators (KPIs) such as unmet SET, repair time, damage quantity, and end-of-life (EOL) emissions were used for evaluation. These metrics enabled a comparative analysis of the façade design cases, which is summarized in the catalogue section. In the following, the methodology used to develop the catalogue was reviewed to assess whether the selected indicators and evaluation methods provided meaningful comparability both across different façade types and among the three performance domains.

The exoskeleton made a big contribution to seismic resilience. However, this also meant that the variations in façade performance themselves were not effectively captured. The existing fragility curve database used for the analysis contained limited data on exterior walls comparable to rear-ventilated systems, which constrained our ability to explore façade-specific variations. Future experimental testing on ventilated façade systems could help supplement knowledge on their seismic performance. The recovery time used for heat resilience assessment did not vary across different design cases; it remained at 25 hours. This was partly due to temperature fluctuations between day and night, which occurred regardless of façade performance. To better capture the influence of different facade typologies on heat resilience during the recovery stage, mitigation measures specific to each façade typology could be implemented.

Introducing a specific technology or component to improve performance in one domain may have trade-offs in another. Therefore, it is essential to assess the added value in one area against its cost in others. In terms of seismic damage, while additional elements introduced some degree of damage, they also helped prevent severe damage, ultimately reducing the required repair efforts. This underscores the need for multi-criteria analysis that considers not only weighting across different domains but also within each domain to ensure a balanced evaluation. For example, allowing a certain level of damage might be acceptable if it significantly reduces repair demands, or alternatively, minimizing initial damage could be prioritized depending on the design intent.

To gain a comprehensive understanding of how different design concepts impact multiple performance domains, a broader design space should be explored. In this deliverable, each design case was evaluated using deterministic attributes based on the most typical or market-ready components. Exploring variability in material properties, component selection, and system configurations could provide deeper insights into optimizing resilience and circularity, ultimately leading to more balanced and effective façade solutions.

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