D5.1

Multi-criteria framework for resilient facades and components

MULTICARE

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1 Introduction

The deliverable 5.1 provides an overarching framework for the assessment and design of resilient and sustainable facades and components. It consolidates the result of task 5.1 and task 5.2. The framework will be applied in the next deliverable 5.2 to inform a catalogue of pre-calculated solutions for the three demo case studies in Bucharest, Amsterdam and Acerra. This framework indicates how to:

(i) Identify the facade system and components for assessment.

(ii) Identify decision-making criteria: compliance-based, environmental, economic, and resilience.

(iii) Evaluate the facade system with compliance-based criteria according to façade design codes and regulations. The facade systems that meets the compliance-based criteria are further evaluated on environmental, economic and resilience criteria.

(iv) Use criteria values from (iii) to conduct multi-criteria analysis, which gives a score for each facade system, enabling direct comparison between facade systems.

Figure 1 provides an overview of the framework. Deliverable 5.1 explains each component in sequential order.

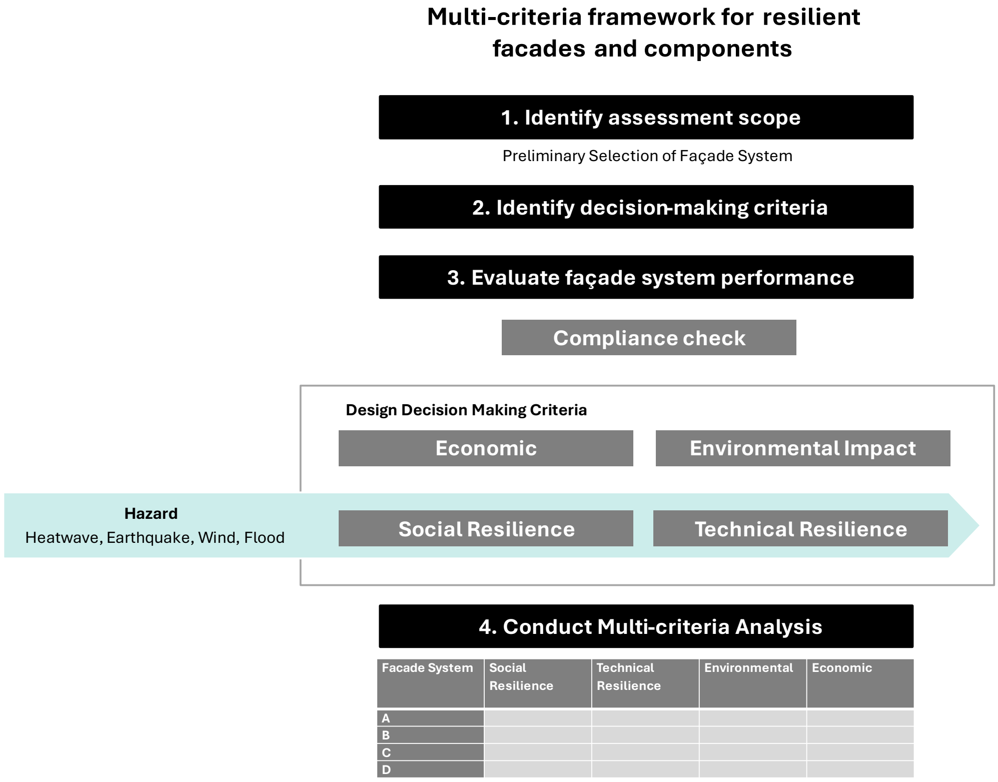

Figure 1 Multi-criteria framework for resilient and sustainable facades and components.

MULTICARE WP5 considers: façade systems, façade components, and façade-structural interface components. While the exoskeleton is part of the structural system and outside WP5's scope, the deliverable 5.1 includes the façade-structural interface, which covers components such as load-transfer brackets. Figure 2 exemplifies this differentiation.

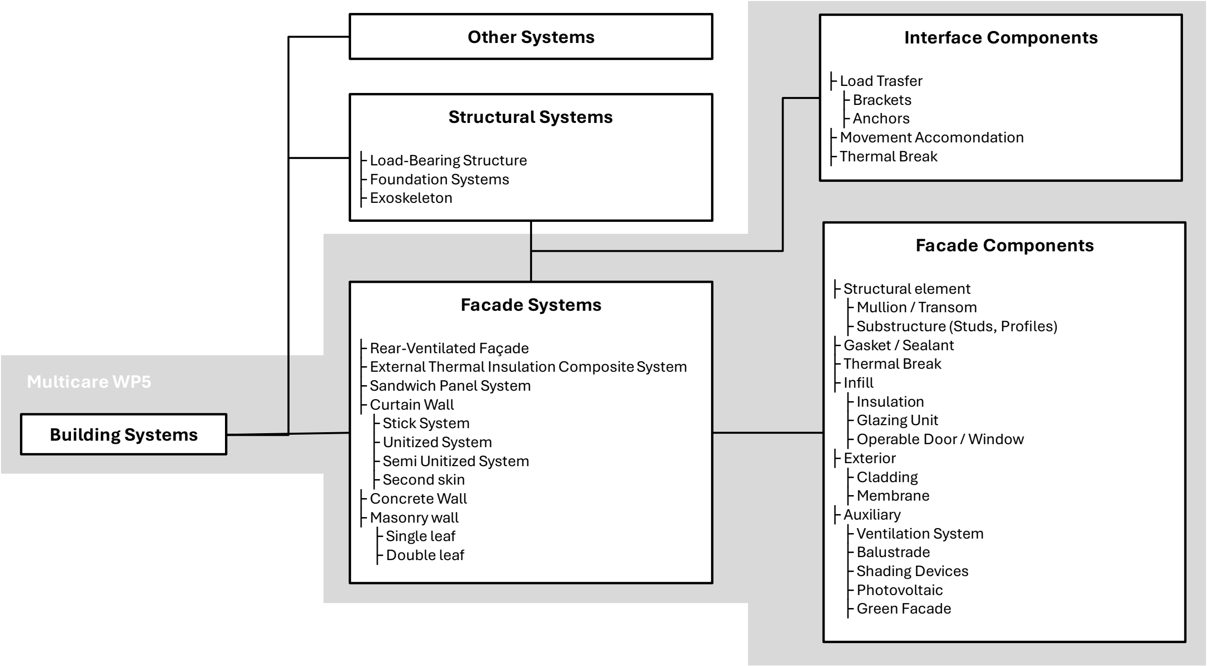

Figure 2 Classification of systems and components with indication of MULTICARE WP5 scope.

Facade Systems

Facade systems commonly found in the European context are categorized into six distinct types. The definitions and terminology for these systems are as follows:

- Rear-Ventilated Facade

A rear-ventilated or rain screen facade is a cold facade system where the cladding elements are mounted on a substructure attached to a load-bearing wall. This design separates insulation from cladding, creating a ventilated space that prevents moisture buildup, regulates temperature, and protects the building from environmental elements.

- External Thermal Insulation Composite System (ETICS)

An external thermal insulation composite system is a warm facade system where an additional layer of insulation is directly applied onto the primary wall of the building. An additional layer of finishing, typically plaster, is applied to the insulation to protect them from external factors such as moisture or direct solar radiation.

- Composite Panel

A composite panel, also known as sandwich panel, consists of two main components: the outer layer and a center core. The outer layer on both sides, typically made up of plastic, metal or wood, provides the panel with structural integrity and protection, while the center core serves as an insulation layer which provides the panel with thermal and fire-resistant properties. With the built-in structural integrity, the composite panel can be utilized as a primary wall, as a load bearing structure, or as cladding elements.

- Curtain Wall

A curtain wall system is a non-load bearing facade system which is mounted onto the building structure. It offers a wide range of implementations as both an opaque or a transparent facade. The installation involves the anchors which support the system's dead load and lateral loads. They are typically cast or fastened to the slab edge. The curtain wall system can be classified into three categories based on the installation and fabrication: stick system, unitized system, and a semi-unitized system which is a combination between a stick and a unitized system.

Stick System

A stick system facade is a type of curtain wall in which the frame, consisting of a vertical member (mullion) and a horizontal member (transom), is assembled on-site. The infill components such as glass panels, insulation layer, or claddings are then installed onto the constructed frame. The system offers a high level of design flexibility and is relatively cost effective in comparison to the unitized system but requires longer installation time.

Unitized System

A unitized system is a pre-assembled curtain wall in which the facade panels are prefabricated in a factory or a workshop and delivered on-site as a complete unit. The prefabrication process offers a modular solution which enhances installation time and reduces assembly tolerances.

Semi Unitized System

The semi-unitized system is a hybrid curtain wall system that combines the elements of both the stick and unitized system. The stick system is mounted on-site serving as a substructure frame, while infill elements are prefabricated as a modular system and installed onto the

Second skin

The second skin facade serves as an external layer which is added on to the primary facade. Typically, the second skin facade features elements such as louvers, screens or glass envelopes, which acts as a buffer layer and allows for daylight regulation.

- Concrete Wall

The concrete wall definition as a facade system is defined by the utilization of concrete materials in the construction process, such as cast-in place concrete, concrete slabs and concrete blocks. The concrete wall can function as both primary wall of the building and as cladding materials.

- Masonry

A masonry wall includes the facade system which is constructed with individual building blocks such as bricks and stones held together with mortar. Depending on the construction

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techniques, they can either be used as a load-bearing or non-load bearing structure. This type of wall can serve as a primary wall or simply as a cladding element.

Single Leaf
A single leaf masonry wall is a type of wall construction that consists of a single layer of masonry. This type of wall is often used in buildings where the load-bearing capacity of the wall is not a primary concern.

Double Leaf
A double leaf masonry wall, also known as a cavity wall, consists of two separate walls or 'leaves' with a cavity between them. The external wall or leaf protects against sun, wind, and rain, and basically only supports itself. The inner 'leaf' is the load-bearing wall. The outer wall acts solely as a protective layer against prolonged weathering and the two are generally connected with metal wall ties, rawl plug anchors, or stainless-steel rods

Facade Components
According to ISO 6707-1:2020 [1], building components are defined as units "manufactured as a distinct unit to serve a specific function or functions." All facade systems can be broken down into their component parts, each with distinct functions as follows:

- Structural
  Structural component of the facade system including conventional wooden/steel profile of various section (i.e L-Profile, U-Profile).

- Infill
  Components which are mounted to the frame or substructure and acts as an interface to the exterior (i.e Insulation, Glazing Unit).

- Exterior
  Exterior Cladding component which serves as weather protection/aesthetical functions (i.e tiles, Aluminum Cladding).

- Auxiliary
  Exterior components which adds supplementary function or aesthetical quality to the façade system (i.e Shading Devices, PV panels).

- Gasket / Sealant
  Sealing component which prevent the infiltration of air and water, typically made from flexible materials.

- Thermal Break
  Components made of low-thermal conductivity material which is installed between interfaces of different materials to limit thermal bridges within the facade components.

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2 Defining the Scope for Early-stage Multi-criteria Evaluation of Facade Systems

This section outlines the process for defining the scope for early-stage multi-criteria evaluation of facade systems under multi-hazard conditions. It begins by identifying facade system and components for assessment by narrowing down feasible options for both new and retrofit designs. A case application from the MULTICARE project demonstrates the facade system configuration of the as-built structure and potential retrofit options.

2.1 Preliminary Selection of Facade Systems

Identifying a suitable facade system for a selected site is a crucial first step in the facades and components design. To facilitate this, an early-stage assessment tool was developed as a part of the multi-criteria assessment framework. It provides a systematic strategy in identifying an optimal facade system for a selected site. The evaluation uses a qualitative method to filter applicable facade systems from predefined facade types based on selection parameters.

The selection parameters are derived from MULTICARE's objective as indicated in the Deliverable 4.1 and general requirements used in the preliminary design of facade systems. They also function as input requirements for the three MULTICARE demonstration sites. This chapter describes the selection parameters used in the filtering process to identify a suitable facade system. The order of the selection parameters described below are based on their prioritization level in the selection process.

Design for Disassembly Requirements

The Design for Disassembly potential is a key parameter in the MULTICARE project and serves as a primary criterion. It refers to the capability of a system to be disassembled for maintenance or easily separated for reuse or recycling at the end of its life.

Variable	Definition
Yes	Major parts of the system can be disassembled (i.e. using screw or nuts and bolts)
No	Major parts of the system cannot be disassembled (i.e. adhesive or cement bonding)

Load Bearing Requirement

In modern facade construction, the facade typically supports only its self-load and external forces, with the primary wall or building structure handling other component loads. However, in renovation projects, the facade may replace the existing primary wall, requiring consideration of load-bearing requirements.

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Variable	Definition
Yes	The facade system has load bearing capacity to handle loads from other components
No	The facade system only handles its own self load and external forces.

Building Physics Requirements

The building physics requirement describes the availability of insulation material in the facade system to ensure efficient thermal and acoustical resistance.

Variable	Definition
Yes	The facade system incorporates an additional layer of insulation to provide extra thermal and acoustical resistance.
No	The building physics performance is solely based on the primary wall characteristic

Building Height

The building height determines the applicability of the facade system on the building typology based on their height. This is evaluated by the installation feasibility and the ability of the facade system to withstand the external forces at various levels.

Variable	Definition
High	Buildings exceeding 21 meters in height, usually eight stories or more.
Medium	Buildings with a height between 9 and 21 meters, generally consisting of three to seven stories.
Low	Buildings with a height less than 9 meters, typically single or two-story structures.

Budget

The budget evaluation of the facade system considers the material and installation cost of the facade types. The costs are normalized as cost per square meter and categorized based on range of values.

Variable	Definition
High	€400–€1000+/m^2 (e.g., unitized curtain walls, advanced glass facades, or custom designs).
Medium	€150–€400/m^2 (e.g., insulated panels, bricks, or cladding with thermal breaks).
Low	€50–€150/m^2 (e.g., basic plaster, simple metal panels).

Logistic Zone Available

The logistic zones evaluate the preparation area required by the installation of the facade systems. This includes a qualitative assessment of the space on site required for accessing the site, storing, and assembling the facade prior to the installation. The variables are presented as a range of normalized values.

Variable	Definition

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High	(0.7–1.0) Ample space available for accessing, storing, and assembling facade components. Suitable for large-scale or complex systems requiring extensive on-site preparation.
Medium	(0.3–0.7) Moderate space available, accommodating storage and assembly with some constraints. Ideal for mixed facade systems requiring partial assembly on-site.
Low	(0–0.3) Limited space available for accessing, storing, and assembling facade components. Suitable for compact, prefabricated systems with minimal on-site handling.

The matrix in Table 1 provides a qualitative evaluation of facade systems. Facade systems are listed on the y-axis, while the selection parameters are organized as column headers. This evaluation is documented in a spreadsheet format to facilitate the filtering and selection process.

Table 1 Qualitative evaluation of facade systems based on selection parameters.

Facade System	Design for Disassembly	Load Bearing Requirement	Building Physics Requirement	Building Height	Budget	Logistic Zone Available
Rear Ventilated Facade	Yes	No	Yes	Midrise	Medium	Low
ETICS	No	No	Yes	Midrise	Low	Low
Composite Panel Non-Structural	Yes	No	Yes	Highrise	Medium	High
Composite Panel Structural	Yes	Yes	Yes	Highrise	Medium	High
Curtainwall Stick System	Yes	No	Yes	Highrise	High	Medium
Curtainwall Unitized System	Yes	No	Yes	Highrise	High	High
CurtainWall Semi Unitized	Yes	No	Yes	Highrise	High	Medium
CurtainWall Second SKin	Yes	No	No	Midrise	High	Medium
Concrete Wall Cast-in-Place	No	Yes	No	Highrise	Medium	Medium
Concrete Wall Precast	Yes	Yes	No	Highrise	Medium	High
Concrete Wall Block	No	Yes	No	Midrise	Low	Low
Masonry Single Leaf	No	Yes	No	Midrise	Low	Low
Masonry Double Leaf	No	Yes	No	Midrise	Low	Low

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2.2 Case Application of the MULTICARE solution

Demonstrator Site and Building Description

As a part of the project proposal, three residential buildings in Acerra, Amsterdam and Bucharest were specified as a demonstrator site for the application of MULTICARE solution. These sites can be classified into two main project categories: New built and retrofit projects. As existing buildings function as multi-family apartments, the Acerra and Bucharest demonstrator represents the retrofit scenarios. They will be retrofitted using the MULTICARE solution, which features a non-invasive retrofit strategy involving exoskeletons structure with facade infills, to enhance the building performances and resiliency. The Amsterdam project serves as a newly built scenario for MULTICARE. The new building will be incorporated with a resilient facade system designed to address future challenges. The following section describes the building characteristics used to classify and categorize the structural and facade systems of these buildings in their as-built condition. This classification serves as a basis for selecting the appropriate facade system for the MULTICARE intervention.

Acerra

The building in Acerra functions as a multifamily housing comprising of eight apartments per floor. With four stories and a 215 square meter rectangular footprint, the building is characterized as a medium size building. Constructed in the 1980s, the building features a concrete structure with hollow brick primary wall and single glazing punched window made of wooden frames. Without recent renovations, the building has a relatively low energy performance and requires an intervention with improved insulation. Material degradation from concrete carbonation and reinforcement oxidation is also evident. Located in a residential area, the site offers limited accessibility for large trucks and on-site preparation areas.

Bucharest

The multifamily apartment building in Bucharest is divided into two blocks with incorporated expansion joints. It consists of three stories, with four apartments per level. The building accounts for a total of 600 square meters in footprint and is considered a medium size building. The building features a load-bearing masonry wall made of hollow bricks. The concrete slabs are connected to the walls by concrete belts. The site in Bucharest is in a similar state to the Acerra building, in which major renovations are required to improve the energetic performance. Additionally, due to seismic activity in the area, visible cracks and material deterioration is apparent. Situated in a residential neighborhood, the site also offers limited accessibility for logistics of large items and on-site preparation area.

Amsterdam

The demonstrator building in Amsterdam is a newly constructed residential building. The building is designed in a U-shaped layout surrounding a central courtyard. The site occupies a footprint of 57 m by 36 m covering approximately 2,052 square meters. With a floor-to-floor height of 3.1 m and a total of 6 stories, the Amsterdam demonstrator is classified as a high-rise building. The building features a modular structure system, in which

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the floor slabs, beams and columns are made out of timber. The main structure is supported by a concrete raft on piles serving as the foundation. The facade subjected to the implementation of the MULTICARE solution is located on the south facing facade in the courtyard area. As a newly constructed building, the site offers relatively higher accessibility for logistics and on-site preparation space.

The site conditions and preliminary requirements for the MULTICARE demonstrators were assessed using the preliminary selection procedure detailed in Section 2.1. This process utilized the filter function in Microsoft Excel, applying the parameters listed in Table 1. Table 2 presents the selection parameters applied to the Amsterdam, Bucharest, and Acerra sites.

Table 2 Preliminary selection parameters applied for each demonstrator site.

Site Condition /Requirements	Design for Disassembly	Load Bearing Requirement	Building Physics Requirement	Building Height	Budget	Logistic Zone Available
Amsterdam	Yes	No	Yes	Highrise	High	High
Bucharest	Yes	No	Yes	Midrise	Medium	Low
Acerra	Yes	No	Yes	Midrise	Medium	Low

Given the project's objective in providing a modular facade system to be installed on an exoskeleton system to enhance the building physics aspects of the building, the variables for the Design for disassembly, load bearing requirements and building physics requirements are consistent in the three cases. The project types and building typologies of Acerra and Bucharest are similar, which is reflected in the building height, budget and logistic zone availability parameters. On the other hand, as a new construction, the site in Amsterdam is categorized as a high-rise with a larger logistic zone and a relatively higher budget.

The result of the filtering process is presented in Figure 3. Based on these three scenarios, the filtering process shows that the budget plays a critical role in influencing the selection of the facade system. Due to the similar project requirements and site context, the rear ventilated facade presents itself as the most viable facade system for Acerra and Bucharest. With a relatively higher budget and larger logistic zone, the unitized system and semi-unitized system are identified as two suitable options as a facade system in Amsterdam.

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Figure 3 Selected facade systems for demonstrator projects.

Table 3 summarizes the assessment scope for the MULTICARE case study, outlining the structural systems, facade systems, and facade design properties as input variables, along with the decision criteria used for evaluation. The assessment includes both as-built conditions and MULTICARE interventions. For the as-built conditions, Acerra and Bucharest are evaluated based on their existing structural and facade systems using the decision criteria outlined in Section 3. For the MULTICARE intervention, the cases include Acerra Retrofit, Bucharest Retrofit, and Amsterdam New. These interventions involve design alternatives that modify facade design properties for each selected facade system, which are also evaluated using the decision criteria.

Table 3 Assessment scope for the MULTICARE case study.

			Structural System	Facade System		Facade Design Properties	Decision-Criteria
				Opaque	Glazing		
1	Acerra	As-built	RC Frame	Double Leaf Infill	Single Pane	N/A	-Resilience -Environmental -Economic -Compliance
2	Bucharest	As-built	Masonry	Double Leaf Infill	Single Pane	N/A	
3	Acerra	Retrofit	RC Frame + Exoskeleton	Rear Ventilated	N/A	-Component properties -Movement -Thermal bridging	
4	Bucharest	Retrofit	Masonry + Exoskeleton	Rear Ventilated	N/A		
5	Amsterdam	New	CLT Loadbearing	Semi Unitized	Double Pane		

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3 Decision Criteria for Facade and Components

Figure 4 shows the decision-making criteria addressed in MULTICARE WP5. Facade systems are evaluated for compliance with local building codes and regulations. Facade systems that meet these compliance-based criteria undergo further evaluation through the MULTICARE enhanced criteria, which examine the entire life cycle across five phases: Initial Construction, Operation, Maintenance, and Demolition. The evaluation considers material and fabrication costs during the initial construction phase, as well as the global warming potential across all life cycle phases. When hazard considerations are included, the assessment incorporates resilience criteria along with additional economic and environmental criteria related to hazard impacts.

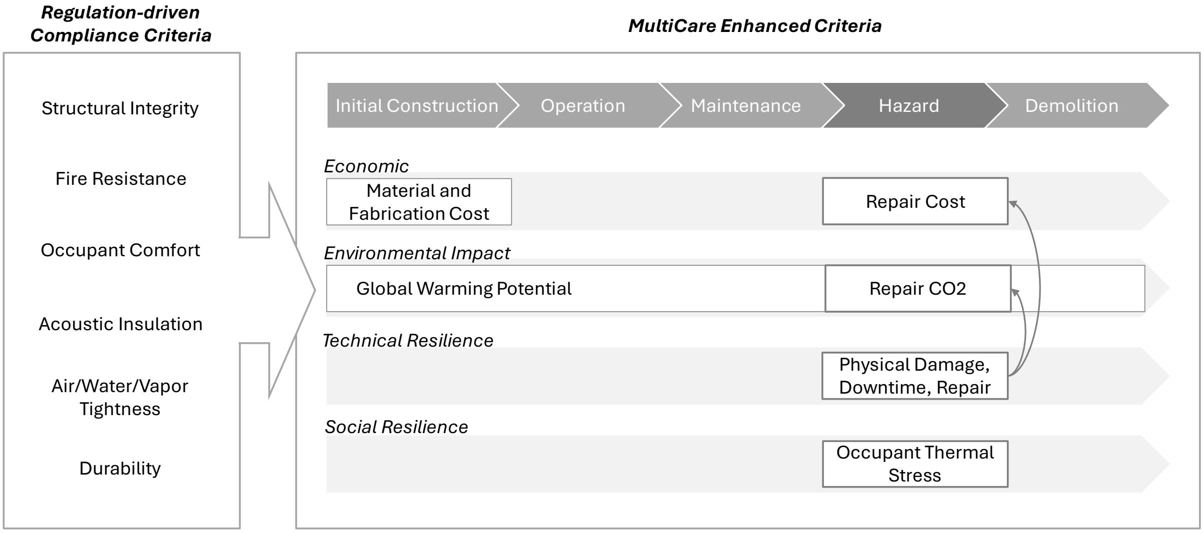

Figure 4 Decision-making criteria in MULTICARE WP5 for facade system evaluation across life cycle phases.

Resilience is considered as the capacity of a system (i.e. a building) to withstand extreme events and “bouncing back”, in other words swiftly recover from the potential losses or damages. Resilience encompasses four interrelated dimensions: technical, organizational, social, and economic [2]. The technical domain relates to how well a physical system performs in terms of structural safety or environmental performance e.g. water tightness. The organizational dimension concerns how institutions manage and take action, but this dimension is out of the scope of this deliverable. The social dimension focuses on measures that reduce negative impacts on communities when critical services are disrupted during an event. The economic dimension addresses the reduction of both direct and indirect financial losses.

Different extreme events inherently emphasize certain dimensions - heatwaves primarily affect human health and comfort as part of the social dimension, while earthquakes mainly cause physical and structural damage which relates to the technical dimension and also

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social losses i.e. casualties. However, both can lead to indirect financial losses e.g. downtime of office or manufacturing space due to heat wave or earthquake. Thus, recognizing the interconnectedness of resilience dimensions is just as important as acknowledging the primary impacts of specific hazards. Integrating metrics across multiple domains ensures a comprehensive design strategy that addresses both the main impacts of specific extreme events and ensures broader system resilience across all dimensions.

Incorporating resilience into decision-making process requires the identification of design criteria to evaluate different facade options. To assess facade design performance in terms of resilience, we propose resilience criteria in Table 4 for each of the phases of an extreme event. These criteria measure different aspects of resilience, organized by hazard type, resilience dimension, and resilience phase. The resilience phases are defined in relation to which phase of the event is considered: resistance is the phase from the start of the extreme event to the peak condition, the robustness is the phase where the maximum or full damage / effect of the hazard is taking place, the recovery is the phase that starts at the end of the extreme event. The next sections explain in detail the reasons for selecting these resilience criteria.

Table 4 Resilience criteria for facade and components.

Hazard Type	Resilience Dimension	Resilience Phase	Resilience Criteria
Heatwave	Social	Resistance	Time to reach first time SET critical [h]
	Social	Robustness	Cumulative degree hours above SET critical [°h]
	Social	Recovery	Time to return to SET critical [h]
Earthquake, Wind, Flood	Technical	Response	Mean Annual Frequency of Exceedance of Damage State [1/years]
	Technical	Recovery	Downtime [months]
	Economic	Recovery	Repair Cost [cost/m2]
	Environmental	Recovery	Carbon emissions [kg CO2e]

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3.1 Social Resilience Criteria

In this framework, social resilience is mainly considered as “thermal resilience”, since social losses that can arise from other hazards than heat waves are only considered at building or urban level.

Thermal resilience refers to a building’s ability to maintain a comfortable and/or safe indoor thermal environment for occupants throughout its lifetime, particularly during extreme weather events caused by climate change (i.e. heat waves) or disruptions like power outages [3]. While thermal comfort is related to the state of mind where occupants feel satisfied with the thermal environment, MULTICARE focuses on the safety aspect, in other words in maintaining thermal conditions that do not pose a heat stress risk on occupants. Safe indoor environmental conditions for health are often defined based solely on ambient air temperature [4]. However, this singular focus is inadequate, as factors such as air movement, humidity, and mean radiant temperature (MRT) play a significant role in influencing heat stress. Overlooking these variables in regulations and guidelines can have substantial implications. For example, air movement offers a low-cost and energy-efficient way to reduce heat stress without needing to lower the air temperature. However, standards that only set a maximum air temperature limit do not account for the advantages that air movement can provide.

To better address these complexities, in accordance with previous work from researchers of the Center of the Built Environment (CBE) [5], MULTICARE heat resilience assessment utilizes the concept of "standardized temperature," which represents a baseline environmental condition with still air, 50% relative humidity, and MRT equal to the air temperature. By employing the standard effective temperature model (SET) [6], the equivalent air temperatures for different combinations of air movement, humidity levels, and MRTs to can be then calculated to ensure an equivalent thermal load on the body as the standardized conditions.

The Standard Effective Temperature (SET) is used as an indicator to evaluate occupants' thermal comfort and response to heatwaves. SET represents the dry-bulb temperature in a hypothetical environment with 50% relative humidity, assuming appropriate clothing is worn [6].

The thermal behaviour of a building during an extreme heat event is a dynamic phenomenon, where the thermal environment changes in time depending on the thermal mass and adaptive capacity of a building and the variations in outdoor weather. When considering the temporal evolution of an extreme heat event, we can recognise three distinct phases, as described by Attia [7]: resistance, robustness, and recovery. The definitions of these three phases are reported below and in Figure 5.

- **Resistance** stage refers to the building system’s ability to maintain its initial design conditions under both typical and extreme weather, relying on coping strategies that prevent critical conditions.

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- **Robustness** stage begins when these coping strategies fail, and the building system and occupants must adjust and adapt to the prolonged stress of the event.
- **Recovery** is the stage where conditions return to the original state following the event.

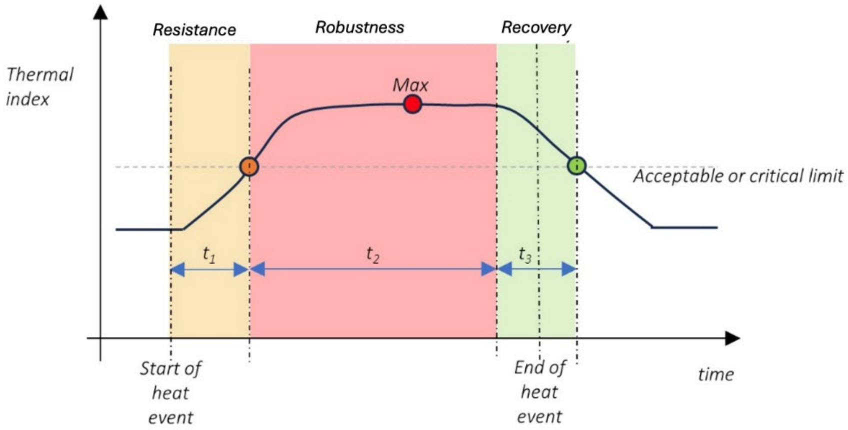

Figure 5 The three temporal phases of thermal resilience: resistance, robustness, recovery.

Table 4 outlines the criteria for assessing social resilience with a focus on thermal resilience during heatwave events. Heatwaves are defined here as periods when the maximum daily temperature exceeds the 90th percentile for at least three consecutive days [8].

In the resistance stage, thermal resilience is measured as the time it takes to reach the critical SET at the start of a heatwave. During the robustness stage, it is assessed by the cumulative degree hours above the critical SET throughout the heatwave. Finally, in the recovery stage, resilience is evaluated by the time needed to return to the critical SET after the heatwave ends.

In terms of maximum safe temperature, following Huizenga et al., [5] MULTICARE utilizes the value of SET of 28 °C for healthy users and three air speeds (still air, 0.4 m.s and 0.8 m.s), which related operative temperature depends on the air velocity. For example, with 0.4 and 0.8 m/s air speed, 50% RH, the indoor temperature limits are 30.1 °C and 31.2 °C respectively. Please refer to tailored and fit-for-purpose thresholds in case of vulnerable populations or standards or public policy recommendations for health when available.

The importance of façade characteristics for thermal resilience has been already demonstrated by previous work, especially in buildings without active cooling or under the risk of power outages. There is a large potential for designing building envelopes that can effectively mitigate the impact of extreme heat events and reduce the needs for active cooling strategies. The impact of façade has been quantified by previous work to range between 10% to 62% in terms of improvements of heat resilience.

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3.2 Technical Resilience Criteria

The technical dimension of resilience examines how physical systems, and their components perform under shock conditions. Non-structural components (NSCs) are elements that aren't part of the building's load-bearing system but still experience dynamic forces and deformation. Performance levels for NSCs can be defined based on the extent of hazard-induced damage. According to FEMA 389 [9], the performance levels and damage states for non-structural elements during earthquakes are:

- Operational Level: Negligible damage; components remain fully functional.
- Immediate Occupancy Level: Minor damage occurs, but cladding, ceilings, mechanical, and electrical components remain secured.
- Life Safety Level: Extensive damage occurs but poses no threat to occupants.
- Collapse Prevention: Severe damage occurs with potential falling hazards.

Response

The extent of damage serves as a performance measure for NSCs during the response phase. These damage levels can be assessed using the Mean Annual Frequency of Exceeding Damage State (MAFE_DS)—a metric that quantifies how frequently a particular damage state is reached or exceeded. MAFE_DS combines two key elements: a hazard curve and a fragility curve. The hazard curve shows the yearly probability of exceeding different hazard intensities, representing intensity measures (e.g., PGA, Wind Speed, Flood Depth) for each return period (MAFE=1/return period). The fragility curve indicates the probability of reaching specific damage states at given EDP levels. The approach uses Engineering Demand Parameters (EDP) differently for earthquakes, floods, and wind. EDPs measure structural responses to hazards and set damage state thresholds. As shown in Table 5, the specific EDP choice varies based on both the type of NSC and the hazard being analyzed.

For earthquakes, Interstory Drift Ratio (IDR) is the primary measure for drift-sensitive NSCs like cladding, glazing systems, and partition walls. Permanent residual displacements (measured also as residual drift ratio) can increase repair or replacement costs when buildings settle in altered positions, leading to jammed windows and compromised weather tightness [9]. For wind loads, pressure on the building envelope serves as the EDP for surface effects and understand damage to windows and facades, while relative floor displacements measure are used to determine the maximum sliding of facades. The shape of the floor displacements is also related with the structural system (i.e., frame systems impose a different displacement to the façade compared to wall systems). For flood events, important parameters are the water depth (i.e., the depth of water forecasted at the site), flood duration, and flow velocity. Depending on the typology of flood event (e.g., flash flood) different damage pattern as well as recovery time might occur. That also relate to the response of the building in terms of water tightness of the building envelope and the water intrusion in the building.

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Table 5 Engineering Demand Parameter (EDP) Choice Based on Non-Structural Component (NSC) Type and Hazard Being Analyzed

Hazard Type	EDP	Impact Mechanism	Relevant NSC Types
Earthquake	Interstory Drift Ratio	Displacement	Partition walls, glazing, curtain walls
	Peak Floor Acceleration	Displacement, Overturning	Suspended ceilings, mechanical/electrical equipment
Wind	Pressure	Displacement, Uplift	Cladding, anchors, fasteners
	Interstory Drift Ratio	Displacement	Curtain walls, glazing systems, ceiling systems
Flood	Water Depth	Water Ingress	Water-sensitive components (electrical systems and equipment)
	Flooded Surface Area	Water pressure and Infiltration	Impact-sensitive components (exterior walls, solar panels, shading devices)
	Resistance of Building Envelope	Impermeability	Waterproofing-sensitive components (windows, doors, joints)
	Flow Velocity	Erosion	Erosion-sensitive components (exterior cladding, foundations, anchoring systems)
	Flood Velocity	Impact	Debris could impact the envelope and damage windows, facilitating water intrusion

Recovery

During the recovery phase, damaged components undergo repairs to achieve three recovery states: re-occupancy, functionality, and full recovery. Performance in this phase is measured through downtime and environmental impacts at different damage levels. Downtime includes two parts: the initial delay before repairs can start and the actual repair duration needed to reach the recovery state. Several impeding factors can delay the start of repairs, including post-event building inspection, financing, engineering services, component redesign, and permit acquisition. These delays vary depending on the hazard type—floods require water recession, while wind events need debris clearing.

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3.3 Environmental and Sustainability Criteria

The criteria in this category cover negative environmental impacts of different materials and façade components in terms of detrimental emissions or contaminations to the environment. The framework serves as an essential tool for supporting informed decision-making, which leads to more sustainable designs throughout the entire building's life cycle. Environmental assessments require a complex holistic approach that spans from raw material acquisition to final disposal or end of life, in accordance to the principles of the Circular Economy.

The comprehensive approach is directly aligned with the MULTICARE mission of generating future-proof, resilient, cost-effective, sustainable, safe, and comfortable solutions. In that sense, the Environmental/Sustainability Criteria is built upon a solid framework that allows uniform and consistent evaluations across all MULTICARE solutions, considering predetermined and quantitative parameters.

A powerful and widely used tool to perform such evaluations is the Life Cycle Assessment (LCA). It can be defined as the process of evaluating the inputs, outputs, and environmental impacts of a facade system throughout its life cycle [10]. The general principles and frameworks for LCA are established by ISO 14040:2006 [10] and ISO 14044:2006 [11]. These standards are complemented by sector-specific international and regional regulations.

There are several standards that revolve around the building sector. ISO 15643:2021 [12] provides principles and requirements for the assessment of environmental, social and economic performance of new construction works over their entire life cycle, as well as existing construction works over their remaining service life and end of life stage. ISO 21930:2017 [13] outlines the specifications to develop an environmental product declaration (EPD) for construction products, services and elements. Furthermore, EN 15804:2012 [14]structures the core product category rules to ensure that all EPDs are derived, verified, and presented in a harmonized way. It establishes the core environmental indicators, units, and models to be used during environmental product declarations. EN 15978:2011 [15] specifies the calculation method, processes, and stages to be accounted for during the environmental performance assessment of new buildings and refurbishments.
Based on the above-mentioned standards and regulations, environmental assessments can be divided into five main life-cycle stages:

- Product stage (A1-A3) includes the raw material extraction, its transportation to the factory, and the manufacturing process.
- Construction Stage (A4-A5): covers all processes from the factory gate of the different construction products (transportation) to the practical completion of the construction work (installation into the building).
- Use Stage (B1-B7): comprises the processes from the practical completion of the construction work to the point of time when the building is deconstructed/demolished. It considers the impact on the building fabric, such as maintenance and replacement, as well as operational energy and water use.

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- End of Life Stage (C1-C4): begins when the building is decommissioned and is not intended to have any further use. It provides a set of materials, products, and building elements to be discarded, recovered, recycled, or reused.
- Beyond the building life cycle stage (D): spans potential resources for reuse, recycling and energy recovery. It incentivizes a loop in components and materials, thereby promoting a circular economy.

The five main life-cycle stages and well as their activities and processes are showcased in Figure 6.

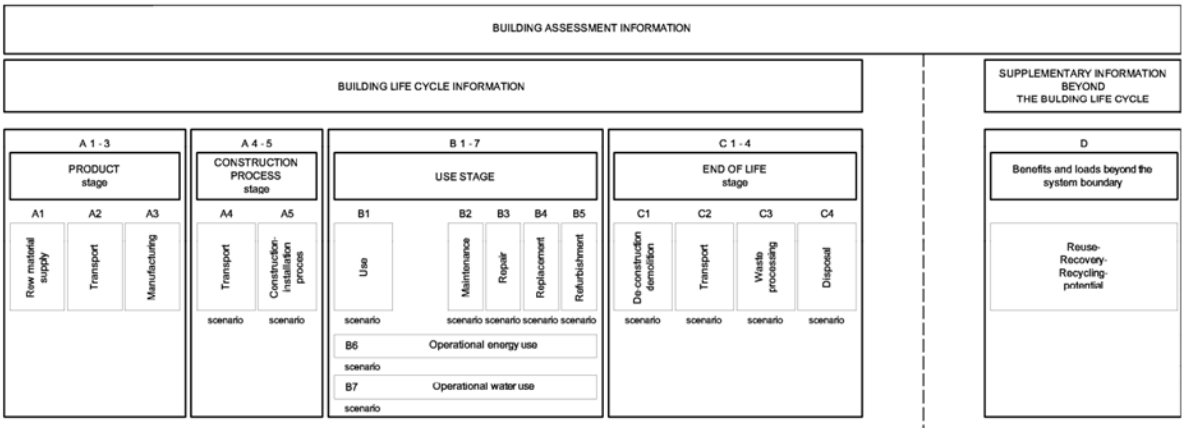

Figure 6 Life cycle assessment stages as established by EN 15978:2011.

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3.4 Economic Criteria

Building facades are essential to a building's aesthetics, functionality, and environmental performance, often making up 15–40% of total construction costs in new projects [16]. These costs depend on materials, system types, and design complexity. Refurbishment costs vary based on the condition of the facade, restoration needs, and updated code requirements.

In the MULTICARE project, material, fabrication, and installation costs are key factors, as shown in Figure 7. Material costs, including glass, aluminium, timber, and insulation, form a major part of the initial investment. The choice of materials must balance affordability [17], [18], performance, and sustainability to meet project goals. Installation costs, including labour and equipment, also play a crucial role in the facade's economic feasibility.

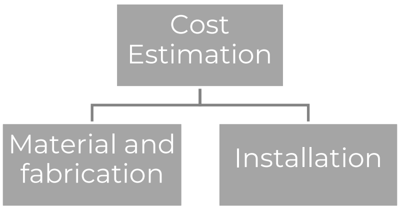

Figure 7 Cost estimation criteria.

Cost of material and fabrication

Material costs refer to the expenses associated with purchasing the raw materials needed to build the facade, such as glass, aluminum, timber, insulation, or steel. Fabrication costs involve the processing, cutting, shaping, and assembly of these materials into the required components before they are ready for installation. Together, material and fabrication costs are a significant part of the overall construction budget [19].

Cost of installation

Installation costs encompass the expenses associated with the labor and equipment required to physically install the facade system. This includes the cost of skilled labor, scaffolding, machinery, and tools, as well as the time required to complete the installation. Complex systems or difficult access conditions may increase installation costs.

Limitation of cost consideration

Since the design is not yet finalized and suitable options are still being evaluated, the main focus is on estimating the approximate material costs. This approach helps identify different options that impact overall expenses. At this stage, the emphasis is on material selection, rather than the installation costs of the facade, to gain an early understanding of the cost implications.

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3.5 Regulation-driven Compliance Criteria

The facade is a complex system that acts as an interface between a building's interior and exterior. It serves multiple functions, including regulating indoor environmental quality, providing a protection layer for the building, and defining its aesthetic features. As a multifaceted system, the functions and performance of a facade have a significant impact on various aspects of a building. These aspects were taken into account in the development of the multi-criteria framework.

Table 6 presents the preliminary design criteria related to the facade performance. This information is derived from the facade performance and characteristics described in EN 13830:2015 [20] along with the facade function diagram developed by Klein [21]. The table classifies the facade performances into seven categories and references them to the design criteria along with relevant design codes.

Table 6 Regulation-driven facade compliance criteria.

Performance Type	Load	Performance Criteria	Relevant Facade Design Code
Structural Integrity	Wind	Deflection	EN 13116 - Resistance to wind load
Structural Integrity	Seismic	Floor Acceleration	Eurocode 8 (NEN-EN 1998-1-2:2023)
Structural Integrity	Seismic	Story Drift	ASCE7-10 Allowable Drift Limit
Fire Resistance	Fire	REI (Stability, Integrity, Insulation)	EN 1991-1-2:2004
Occupant Comfort	External Temperature	Thermal Transmittance	UNI 10077-1, UNI EN 13947:2007
Acoustic Insulation	Sound Pressure Level	Weighted Sound Reduction	DPCM 5/12/97
Air Tightness	Wind Pressure	Class of Air Infiltration	UNI EN 12153 - Air permeability
Water Vapor Tightness	Rain Intensity	Vapor Resistance	UNI EN ISO 13788
Durability	External Temperature, Rain Intensity, Solar Radiation	Estimated Service Life	UNI 11156,2006

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4 Assessment Methods for Resilience and Carbon Footprint

4.1 Social Resilience Criteria Assessment

Figure 8 shows the workflow for the assessment of the heat resilience (social resilience) of facade systems. First, location and assessment scopes are defined. Secondly, the assessment process is performed by: 1. Considering the heat hazards events of relevance; 2. A simplified geometry informed by a shoebox model; 3. The related enveloped characteristics to assess.

The simplification at the level of the shoebox model is suggested for preliminary analysis, for comparative purposes across multiple solutions. If a design is already elaborated, it is suggested that the elaborated geometry is incorporated to consider for weighted indicators for floor elements.

The social resilience is then quantified as described in previous section, by considering the temporal evolution across the three phases i.e. resistance, robustness and recovery with the SET metric as a threshold. As pointed out in the previous sections, the value of SET threshold depends on the vulnerability of the person. Based on current evidence from literature, It is currently defined at 28°C. However, it is strongly recommended to follow updates in comfort and health research for better and more specific threshold depending on the vulnerability of the users and the building functionality.

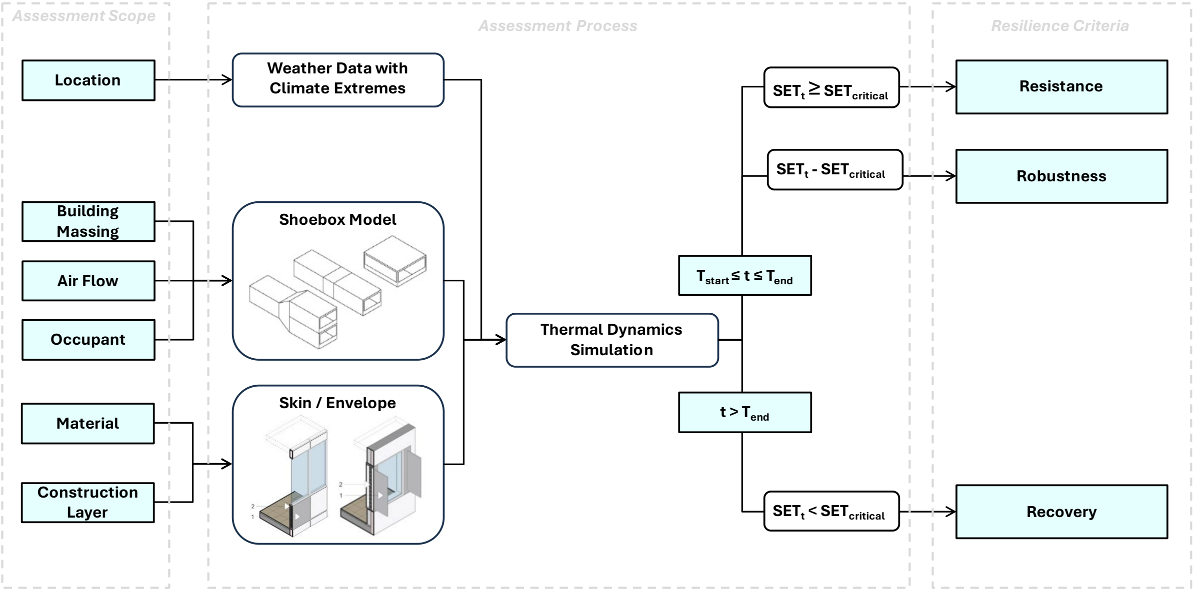

Figure 8 Schematic diagram of the simulation-based workflow for deriving social resilience criteria

Annual frequency of exceedance (AFE) of heatwave intensities

Creating a heatwave hazard curve involves analysing historical and stochastically generated future weather data to estimate the annual frequency of exceedance (AFE) for different intensity level of heatwaves. The following steps outline the procedure:

1. Define the heatwave intensity measure (IM) and threshold
   The first step is to define the intensity measure and the criteria for identifying heatwave events. Metrics used to characterize heatwave severity include Mean daily temperature, Heatwave duration, and Peak temperature. When using daily mean temperature (Tmean) as the primary metric, a common threshold for a heatwave is the 95th percentile of Tmean over a reference period.

2. Identify the weather file format to be used for thermal simulation
   Thermal simulation requires weather data in a specific file format. The EnergyPlus Weather File (EPW) is used for running EnergyPlus [22]. It contains hourly data for an entire year (8,760 data points), including key meteorological parameters: temperature, relative humidity, wind speed, and solar radiation.

3. Collect climate weather data, extract heatwave events, and convert to EPW file format
   - Historical data: Obtain daily temperature records from 1970-2024 using the National Oceanic and Atmospheric Administration (NOAA) dataset [23] or European Climate Assessment Dataset (ECAD) [24]. Identify heatwave events from these temperature records, then convert the years containing heatwaves into EPW file format.
   - Future data: Use generators like the Multi-scenario Extreme Weather Simulator (MEWS) [25] to create future extreme weather EPW files directly. Use the collected historical data as input to generate predictions for 2024-2030.

4. Calculate exceedance frequencies
   For each intensity level, count the number of heatwave events exceeding the threshold. Divide the count of exceedance events by the total number of years in the data set.

Selection of Façade Properties for Thermal Resilience Assessment

The influence of facade design parameters on indoor thermal resilience remains a relatively unexplored area of research. Research conducted within MULTICARE WP5 established a procedure for selecting façade properties for thermal resilience assessment. The detailed procedure are shown in Figure 9.

The workflow recommends performing a sensitivity analysis depending on the building geometry and the future weather characteristics. It is recommended to consider an uniform distribution of key façade parameters, since during the design phases any value can be selected. In Table 7, a list of key parameters to consider and their potential distribution is suggested, however these ranges can be tailored to specific local construction requirements. For instance, the lower bound of the parameter “thickness of the insulation layer” can be adjusted to contain the minimum level required for compliances with local energy efficiency regulations.

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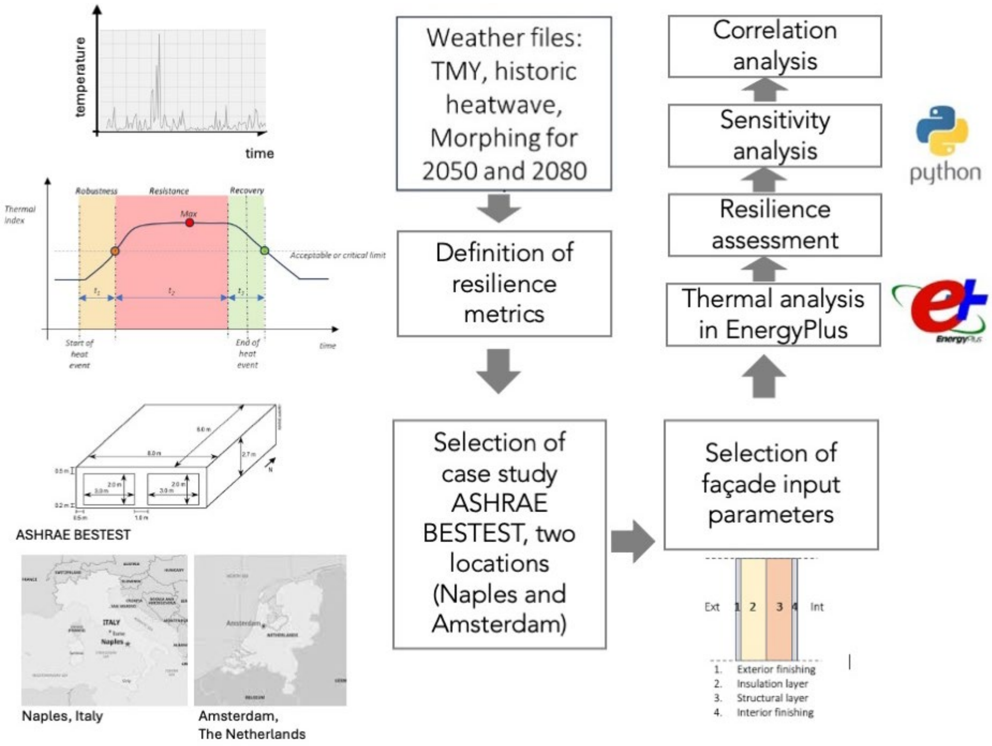
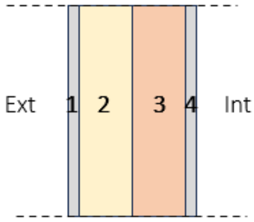


Figure 9 Overall workflow of the assessment, encompassing: future and historic weather data creation, definition of resilience metrics, selection of case study and geometrical input, definition of facade input parameters, building performance simulation (BPS) in EnergyPlus or similar thermal simulation models, computing of resilience indicators and sensitivity analysis in Python or other programming language of preference. .

Table 7 Material and geometrical specifications utilized for the sensitivity analysis.

Layer	Range in properties	Distribution	Facade layers
Specific heat in layer 3	400-5000 [J /kg K]	Uniform	 1. Exterior finishing 2. Insulation layer 3. Structural layer 4. Interior finishing
Density of layer 3	250 / 5000 [kg/m^3]		
Exterior finishing solar absorptance (layer 1)	0.1-0.95 [-]		
Thermal conductivity of the insulation layer (layer 2)	0.02-0.5 [W/m K]		
Thickness of the insulation layer (layer 2)	0-0.50 [m]		
Thermal transmittance of the window glazing	0.6-6 [K/W m^2]		
G-value of the window glazing	0.1-0.9 [-]		
Infiltration rate	0.5-8 [ACH]		
Vent area	0.1-20 [m^2]		
Window-to-Wall Ratio	3-92 [%]		

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Overall, to enhance robustness, recovery and resistance, low g-values and WWR and large ventilation area should be prioritized. The influence of these parameters has small variations depending on the scenario (future weather scenario or location) but they consistently rank within the top three most influential parameters. An exception is the role of ventilation area in the robustness period where ventilation may be detrimental and decrease the robustness period time, if for instance outdoor air temperature are higher than indoor ones. This highlights the importance of multi-criteria decision making in facade design to balance competing requirements in terms of facade performance and enabling dynamic changes is facades, so that the detrimental impact of g-value and WWR on daylight and view access can be reduced. This is also very relevant when considering the competing requirements of daylight and view access with thermal resilience, as shown by the importance of high g-values and low WWR in enhancing resilience to heat. This is coherent with previous work that emphasized the importance of limiting solar gains and increasing natural ventilation [11] in limiting indoor overheating [26], [27], [28], [29], [30]. As also reported by Breesch et al., thermal mass (here indicated as specific heat capacity and density) was shown to be less important than window-to-wall ratio and SHGC for the overall resilience to heat in current and future climates [30], for insulated buildings and when differences in temperatures between day and night are small or negligible.

An important remark when conducting this type of assessments is the consideration of air velocity when computing the Standard Effective Temperature (SET). If the air velocity around the occupant is assumed to be still, as a conservative approach, then there is the risk of underestimating thermal resilience. Considering higher air velocity, as it is usually the case in natural ventilated buildings, would have a beneficial impact on SET. In addition, the building geometry and the orientation of the facade influence the overall performance requirements of the facade. Finally, in this deliverable only the vertical façade is considered, however, the approaches presented can be expanded to consider the roof, which has a key impact on building resilience.

Shoebox Modeling for Evaluating Facade-Specific Thermal Resilience

The shoebox model for assessing a facade system's thermal resilience abstracts building-level impacts. While aggregating damage data across floors is effective for structural assessments, social resilience evaluation requires a more nuanced approach, as human impact cannot be meaningfully captured through simple aggregated metrics. The shoebox model captures worst-case scenarios, such as conditions on the topmost floor or highly exposed south-facing facades. By translating occupant profiles and behavioral patterns from various building zones into a representative occupant model within the shoebox zone, it can accounts for diverse user needs. Parameters such as window-opening patterns and temperature setpoints are assumed to be consistent across all building zones.

Annual Resistance, Robustness, and Recovery

The discrete points in the hazard curve correspond to the weather files used in the analysis. Thermal simulations are performed for all weather files in combination with the zone settings defined by the shoebox model and the envelope specifications.

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The simulation outputs are processed to calculate resistance, robustness, and the recovery phase, using the temporal outcomes of the SET (SET_t). From the year-long simulation, the temporal frame for a heatwave is identified, where $T_{\mathrm{start}} \leq t \leq T_{\mathrm{end}}$ represents the heatwave period, and $t > T_{\mathrm{end}}$ marks the post-heatwave recovery phase. For this timeframe:

1. Resistance: Defined as the duration from the starting timestep of the heatwave (T_{start}) until the time when SET_t first reaches or exceeds the critical threshold $\mathrm{SET}_{\mathrm{critical}}$.

$$\mathrm{Resistance} = t_{\mathrm{critical\ onset}} - T_{\mathrm{start}}, \quad \mathrm{where} \quad \mathrm{SET}_t \geq \mathrm{SET}_{\mathrm{critical}}$$

2. Robustness: Measured as the cumulative degree-hours above the critical threshold during the heatwave period.

$$\mathrm{Robustness} = \int_{T_{\mathrm{start}}}^{T_{\mathrm{end}}} \max(0, \mathrm{SET}_t - \mathrm{SET}_{\mathrm{critical}})\, dt$$

3. Recovery: Defined as the duration from the ending timestep of the heatwave (T_{end})until the time when SET_t drops back below $\mathrm{SET}_{\mathrm{critical}}$.

$$\mathrm{Recovery} = t_{\mathrm{recovery}} - T_{\mathrm{end}}, \quad \mathrm{where} \quad \mathrm{SET}_t < \mathrm{SET}_{\mathrm{critical}}$$

Using the hazard curve probabilities and simulation outcomes, the annualized values for resistance, robustness, and recovery stage are calculated by multiplying each metric by its corresponding annual probability of occurrence. The equation for the annualized resilience loss is:

$$\mathrm{Annual\ Resilience\ Loss} = \sum_{i=1}^{N} P_i \cdot \mathrm{Resilience\ Loss_i}$$

Where:

- P_i is the annual exceedance probability of the i-th weather file (with a total of N weather files) from the hazard curve
- $\mathrm{Resilience\ Loss}_i$ represents the respective metrics for Resistance, Robustness, or Recovery for e ach weather file

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4.2 Technical Resilience Criteria Assessment

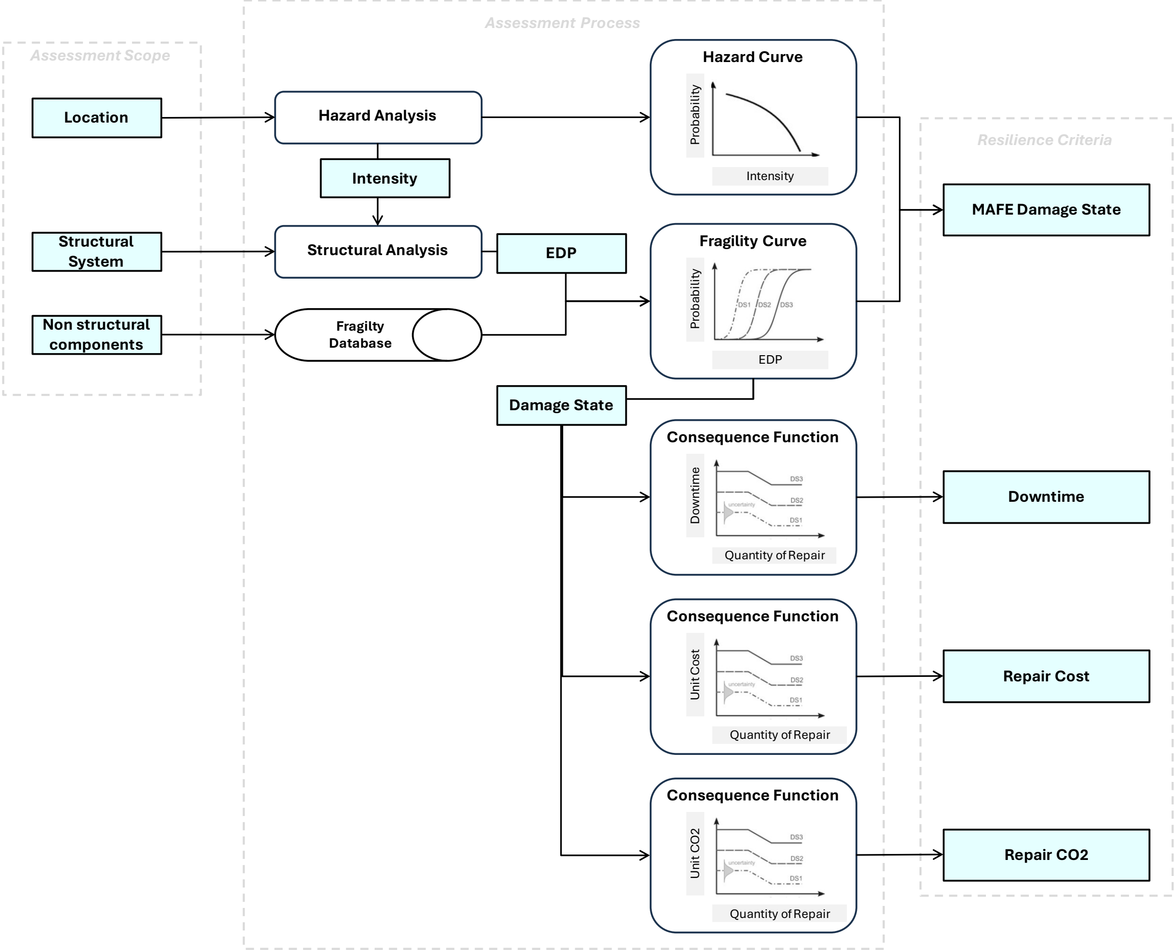

Figure 10 Schematic diagram of the simulation-based workflow for deriving technical resilience criteria.

Mean Annual Frequency of Exceeding (MAFE) Damage State

The mean annual frequency of exceedance of a specific damage state (λ_{DS}) is calculated by integrating the product of the hazard curve and the fragility curve over the range of intensity measures (IM). MAFE can be expressed as:

$$\lambda_{\mathrm{DS}} = \int_0^\infty P(\mathrm{DS} \mid \mathrm{EDP}) \cdot \frac{d\lambda(\mathrm{IM})}{d\mathrm{IM}} \cdot \frac{d\lambda(\mathrm{IM})}{d\mathrm{EDP}} \, d\mathrm{EDP}$$

Where:

- $P(\mathrm{DS} \mid \mathrm{EDP})$ is the fragility function, which gives the probability of exceeding the damage state at a given engineering demand parameter.
- $\frac{d\lambda(\mathrm{IM})}{d\mathrm{IM}}$ is the hazard curve, describing the rate of occurrence of intensity measures.
- $d\mathrm{EDP}$ is the differential of the engineering demand parameter, integrated over all possible values.

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The hazard curve is derived from location-specific hazard data, which relates hazard intensity (e.g., ground motion, water depth, or wind speed) to the annual frequency of exceedance. This curve reflects the likelihood of experiencing various hazard intensities at a given site. Hazard curves are typically obtained through probabilistic hazard analysis, which computes the exceedance rate for each intensity measure as in:

$$\lambda(\mathrm{IM}) = \frac{1}{T_r}$$

Where:

- $\lambda(\mathrm{IM})$ is the annual frequency of exceedance of intensity level
- T_r is the return period associated with the intensity level (e.g., 50, 100, 500 years)

Next, structural analysis provides engineering demand parameters (EDPs), which describe the structural or system response to varying hazard intensity levels. For seismic hazards, methods such as linear dynamic analysis (e.g., modal analysis) or nonlinear dynamic analysis (e.g., pushover analysis) are used to determine EDPs like inter-story drift ratio and peak floor acceleration. For wind hazards, computational fluid dynamics (CFD) and wind pressure analysis provide EDPs such as drift ratio, pressure, and envelope resistance. For flood hazards, hydrodynamic simulations estimate EDPs like immersion depth, flow velocity, and flooded surface area.

These EDPs are then used to access fragility functions, which quantify the probability of exceeding specific damage states. Fragility functions can be sourced from established databases such as FEMA P-58 Non-Structural Component Fragility Functions for seismic hazards [31], HAZUS-MH [32] for wind and flood hazards, or derived from literature and experimental testing for NSCs unique designs or performance criteria not covered by these tools.

Finally, the hazard curve and fragility functions are integrated, as shown in the previous equation, to compute the mean annual frequency of exceedance (MAFE) for the damage state. This calculation encapsulates both the probabilistic nature of the hazard and the structural performance of the facade system.

Downtime

The FEMA P-58 methodology [33] estimates repair time to achieve full recovery. It considers repair sequencing either in series (floor-by-floor) or in parallel (all floors simultaneously). The REDi guidelines [34] incorporate impeding factor delays before repairs begin, covering re-occupancy, functionality, and full recovery states. By defining the sequencing of structural and nonstructural repairs and the recovery states, the total downtime can be calculated using FEMA P-58 to estimate repair time per component and damage state, while the REDi guidelines provide a basis for accounting for impeding factors.

Repair Costs and Environmental Impact

The damage-to-environmental impact conversion includes three approaches:

1) The repair cost-ratio approach, which calculates repair impacts using pre-use (full replacement) ratios
2) EIO-LCA, which estimates environmental impacts based on repair costs

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3) The repair description + LCA approach, which develops data from detailed damage descriptions.

While the EIO database is designed for the USA and requires extensive adaptation for Europe, the repair description approach, though precise, is resource-intensive and best suited for case-specific studies. Consequently, the repair cost-ratio approach is deemed the most appropriate for this work package to assess hazard-induced environmental impacts.

The consequence model shows the relationship between repair quantities and embodied carbon, evaluating environmental impacts across various damage states. These models are accessible via the FEMA P-58 database using the Performance Assessment Calculation Tool (PACT) [31] or can be custom-developed for specific contexts, such as Italy [35]. To assess seismic repair impacts over a building's lifecycle, time-based assessments, which consider multiple seismic events, are recommended over intensity-based or scenario-based assessments, which focus on single earthquake events [36].

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4.3 Environmental Impact Calculation

The environmental assessment utilizes the total Global Warming Potential (GWP total) as an indicator. It quantifies the carbon footprint across the cradle-to-cradle lifecycle being expressed in $kgCO_2eq$.

Several computer tools have been developed to conduct whole life cycle assessments for buildings, each with its own approach to data input. To address this variability, the process for entering data to estimate the carbon footprint was simplified to its most basic form. This ensures that the method is flexible and can be easily adapted to any tool, rather than software dependent. A bottom-up approach was designed for the data flow and configuration, tailored to the scale of building projects. The process begins with the most fundamental and commonly used element, the “material”, which, in the context of MULTICARE WP5 is equivalent to component. These materials are then combined to form “systems,” and, ultimately, all systems collectively constitute the building as a whole. The designed approach can be seen in Figure 11.

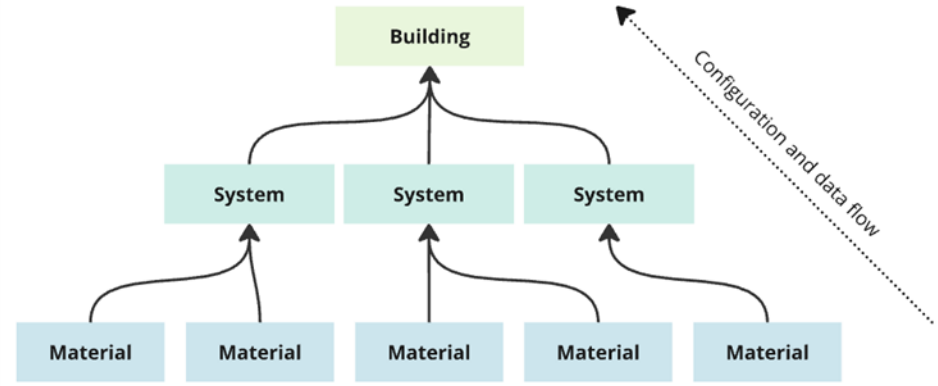

Figure 11 Bottom-up approach to data and configuration.

Life-cycle assessments (LCAs) are inherently complex, making LCA software an effective tool for conducting evaluations. However, users must assess the quality of the data to ensure its accuracy. One key point is to use appropriate carbon footprint databases, as data can vary significantly between regions and countries.
Given this deliverable’s focus on building construction and hazard recovery, the carbon footprint can be divided into two specific scenarios: the “Seamless Life-Cycle Scenario” and the “Recovery Scenario,” both of which are described below.

Seamless Life-Cycle Scenario
The premise for this scenario is that all life-cycle stages occur as planned, without significant disruptions that could alter the building's intended state. It follows a cradle-to-cradle approach that spans all five stages established by EN 15978:2011 as well as its guidelines. Planned repairs, replacements and refurbishments must be included in the calculation of the facade carbon footprint. When evaluating the facade system, the building energy use is not considered since it only affects indirectly building performance.

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A simplified example of the Seamless Life-Cycle Scenario can be found in Figure 12.

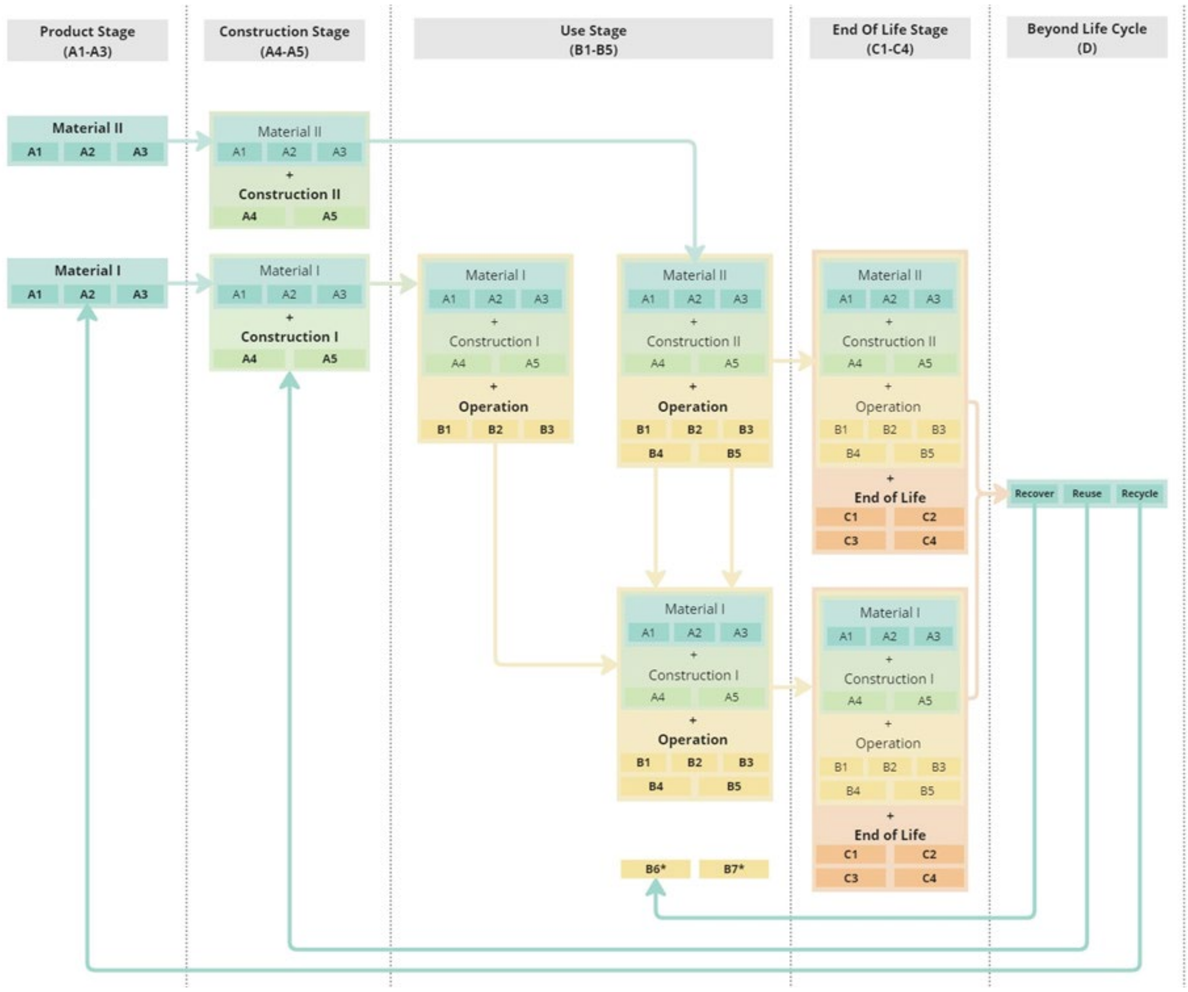

Figure 12 Simplified version of the Seamless Life-Cycle Scenario.

This scenario quantifies the facade's embodied carbon from cradle-to-cradle, in $kgCO_2eq$. The analysis of all five building stages enables users to identify risks and opportunities to foster circularity within the project. For instance, adopting a Design for Disassembly approach significantly impacts the end of life and beyond life-cycle stages and reduces the overall carbon footprint.

Recovery Scenario

This scenario is based on the assumption that an extreme event occurred, necessitating recovery efforts to restore the building to its original condition. It not only measures the whole life-cycle embodied carbon for the facade system, but also enables users to estimate the additional environmental impacts of the building recovery. This covers all LCA stages, from new product manufacturing to disposal/reuse of the damaged elements. Figure 13 provides a simplified example that highlights the carbon footprint of the recovery, compared to the seamless life-cycle scenario.

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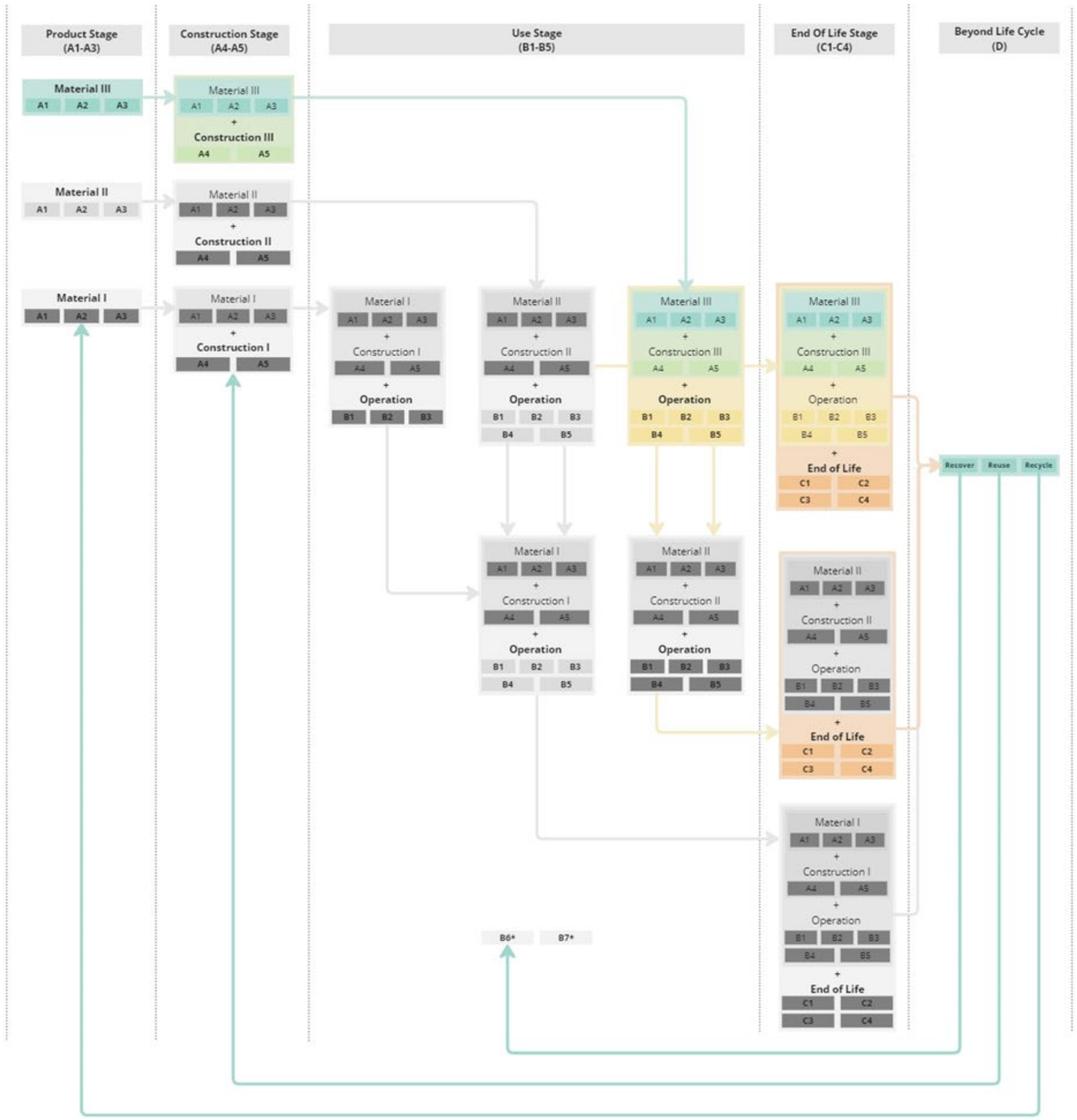

Figure 13 Additional steps of the Recovery scenario (in color) compared to the Seamless Life-Cycle Scenario (in gray).

As mentioned in Section 4.2, three approaches can be followed to assess the damages: the repair ratio, the EIO-LCA, and the repair description to an LCA approach. While the latter leads to a more detailed evaluation of the environmental impacts of the building recovery, it is also very time-consuming. This is deemed fit to specific case studies, in which high-quality data is available, and a thorough impact evaluation was conducted. For general and hypothetical assessments, using pre-use repair impacts the ratio approach is deemed more suitable. Regardless of the user's approach, a detailed and adequate database should be used to estimate the carbon footprint of all elements involved in the recovery process, supporting more assertive assessments.

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4.4 Cost Estimation

The process of cost estimation, as shown in Figure 14, is crucial in understanding the financial implications of the selected facade system. It begins by identifying an appropriate system and analysing its individual components, which collectively contribute to the overall expense. Breaking the facade into distinct layers such as the substructure, brackets, insulation, thermal membranes, and cladding not only provides clarity on material, fabrication, and installation costs but also helps in aligning the facade's design with the project's budgetary constraints. This systematic approach allows for approximate budgeting and enables design optimization by addressing cost-driving factors early in the process.

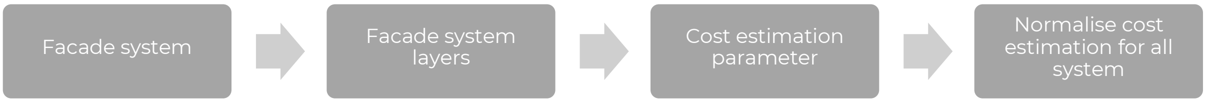

Figure 14 Cost estimation procedure.

1. Selection of facade System

The foundation of cost estimation lies in selecting the most suitable facade system. This step involves the evaluation of typical facade systems as described in chapter 1 [37] including as stick, semi-unitized, rear-ventilated facades, and composite panels. The result of the evaluation determines the suitable facade systems that aligns with the architectural intent and complies with the key performance indicators (KPIs). The selection is guided by the specific requirements of the demo site, such as environmental conditions, structural needs, and desired aesthetic outcomes. This evaluation not only informs the initial choice of the facade system but also sets the stage for a more detailed breakdown of its components, which directly impact the cost estimation process.

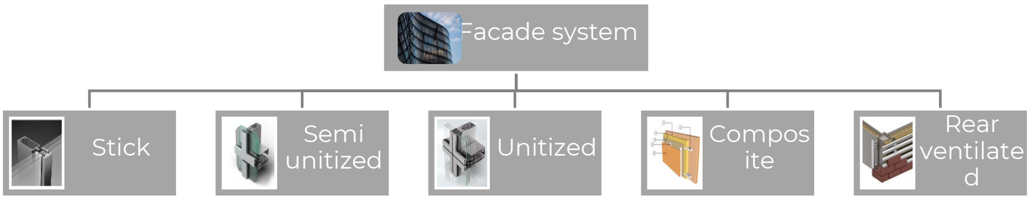

Figure 15 Facade system and its classification.

2. Facade system layers

Once the facade system is selected, the next step is to analyse its structure by breaking it into key layers that serve distinct functions. Each facade system comprises components such as the substructure, brackets, insulation, a thermal membrane, and cladding. This layered breakdown is essential for understanding how each component contributes to the overall cost, as it highlights the interdependencies and variations within the system.

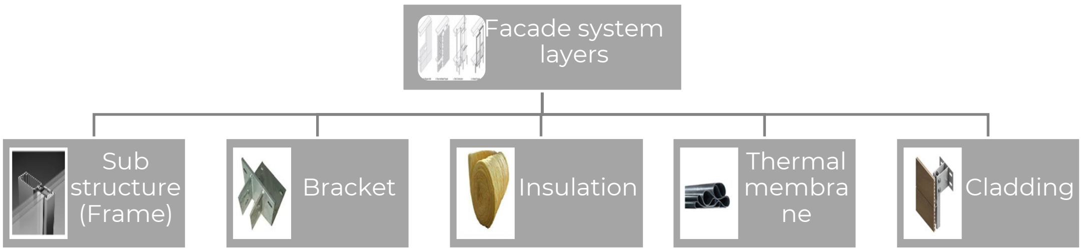

Figure 16 Layers of facade system.

3. Deriving the cost parameters for facade layers

To approximate the cost of a facade, it is essential to identify the cost parameters that influence the selected facade system. Each facade layer corresponds to a specific component or material type, measured by length, unit, or square meter, depending on its application. The process includes referencing materials from the facade catalogue and their associated cost ranges, providing a comprehensive understanding of available options. This streamlined approach establishes a foundational framework for estimating costs effectively.

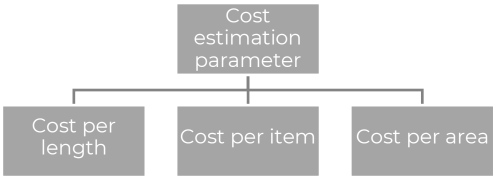

Figure 17 Cost estimation parameters of facade layers.

Table 8 Cost estimation parameters for facade components and estimation methods.

	Facade Components	**Estimation**
Cost per length	Substructure (Frame, T profile, sash)	Price per meter
Cost per unit	Bracket (Steel or aluminum)	Price per item
Cost per area	Insulation	Per meter square
	Membrane	Per meter square
	Cladding	Per meter square

4. Normalize Cost Estimation for all facade systems

Material cost calculation involves normalizing the facade layers across different systems (Figure 15). Each system has distinct construction methods and components (Figure 16) which can complicate cost estimation. To address this, the facade layers are simplified by focusing on a per-square-meter construction area. Key components are identified, as explained in Figure 16. Sections (cost per length, area and unit), leading to the development of a unified formula that represents the cost of a facade system, regardless of its complexity. This approach streamlines the calculation process while maintaining a reasonable approximation.

General Cost Formula:

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In general, the total cost of a facade system is simply the sum of the costs of all materials involved.

Total Cost = Cost of Frame + Cost of Bracket + Cost of Insulation + Cost of Glass + Cost of Cladding

In the following sections, each facade system is simplified into a module, with cost estimates provided for each layer within these simplified modules.

Estimation -Stick system layers

As shown in Figure 18, multiple components of the facade system can be simplified by focusing on the major elements that significantly contribute to cost estimation. For clarity, Figure 18 provides a schematic representation of a stick facade system. In this approach, the cost of non-essential elements, such as the exoskeleton and walls, is excluded to streamline the estimation process and focus on the core facade components.

Figure 18 Stick system, Stick system installation, Stick system simplified.

Cost per length (Frame) Is calculated by considering the framing elements required for one square meter of the facade, typically comprising two vertical frames (mullions) and two horizontal frames (transoms).
Cost per item (Bracket) Brackets are calculated based on the vertical profiles to which they are attached for installation. In this system, each square meter of the facade panel typically includes two vertical profiles, resulting in two brackets, one for each profile.
Cost per area (Glass / cladding) Is determined by the total surface area of these materials within the facade. The cost is based on the material price per square meter.

<u>Normalize number of layers in the stick system</u>

- Fixed Frames – horizontal -2/2, vertical -2/2
- Bracket – 2
- Glass – 1 (per square meter)

Lm, Lt, : Cost of stick frame (per Lengths in meters) of mullions, transoms
Lum, Lut, : Cost of unitized frame (per Lengths in meters) of mullions, transoms

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Ai, Ag, Ac : Cost (per square meter area) insulation, glass, and cladding.
Ub : Cost (per Unit) Bracket.

Total cost = (2×Lm) + (2×Lt) +(1 × Ag) +(2× Ub)

Estimation of Unitized System layers

Similar to the stick facade system, the unitized system consists of frames, panels, and brackets. The key difference is that the unitized system is prefabricated and then installed on-site. To normalize the system a simplified version of the layers is created, which makes it easier to perform the cost estimation (Figure 19).

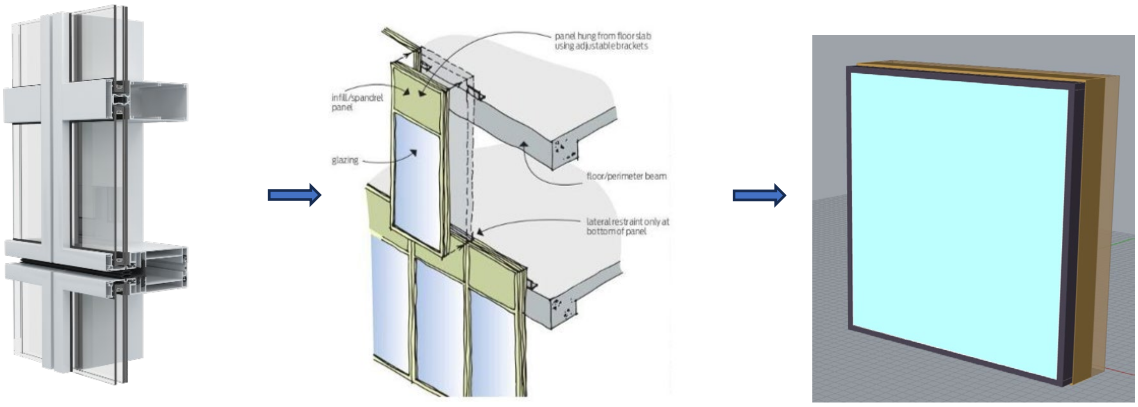

Figure 19 Unitized system, Unitized system installation, Unitized system simplified.

Cost per length (Frame) The cost of the frame is estimated based on its prefabricated design. Each module of the facade generally includes two vertical frames (mullions) and two horizontal frames (transoms). The total cost is calculated by measuring the length of these frames and factoring in material costs.
Cost per item (Bracket) In a unitized system, the calculation of brackets differs due to its construction technique. Here, two panels are connected using male and female frame joints, sharing a single facade bracket. As a result, each panel effectively utilizes half a bracket per vertical profile. For simplicity, this can be approximated to one bracket per square meter of the facade panel if the panel design typically includes two mullions per square meter.
Cost per area (Glass / cladding) is determined by the total surface area covered by these materials within the facade. Glass and cladding elements are calculated based on their respective material costs per square meter, reflecting their influence on the overall expense.

<u>Normalize number of layers in the stick system </u>(Per square meter)

- Frames – horizontal -2, vertical -2
- Bracket – 2
- Glass – 1 (per square meter)

Lm, Lt, : Cost of stick frame (per Lengths in meters) of mullions, transoms

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Lum, Lut, : Cost of unitized frame (per Lengths in meters) of mullions, transoms
Ai, Ag, Ac : Cost (per square meter area) insulation, glass, and cladding.
Ub : Cost (per Unit) Bracket.

Total cost = $(2\times Lm) + (2\times Lt) + (2\times Ag) + (2\times Ub)$

Estimation of Semi unitized System layers

As illustrated in Figure 20, the semi-unitized system combines elements of both the unitized and stick systems, as previously discussed. In this configuration, unitized panels are prefabricated off-site and subsequently installed onto the stick system frame on-site. For simplification, cost estimation can be normalized by considering one square meter of the semi-unitized system panel for calculation purposes.

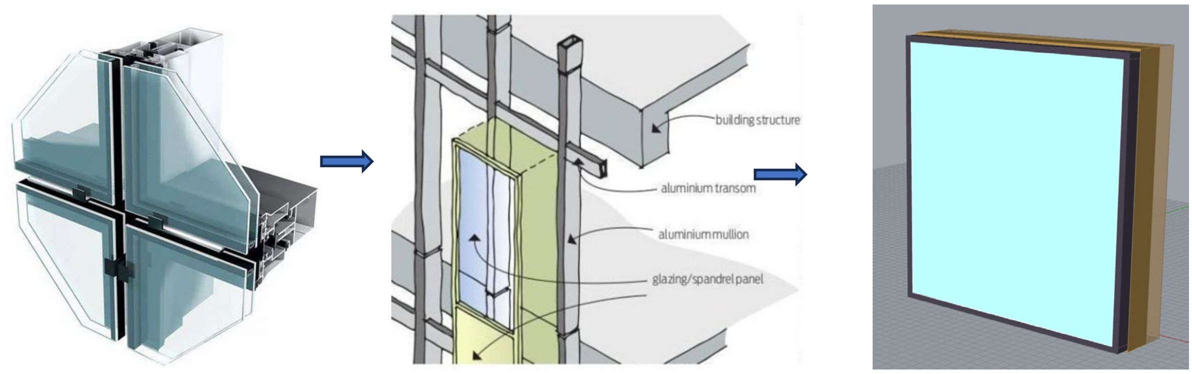

Figure 20 Semi unitized system, Semi unitized installation, Semi unitized simplified.

Cost per length (Frame) To standardize the calculation for one square meter of facade, it can be assumed that the frame consists of two vertical and two horizontal members, providing the structure onto which the unitized panels are installed.
Cost per item (Bracket) This facade pre-assembled unitized panels are fixed onto a stick system frame. The brackets in this configuration are connected to the vertical frames of the stick system, bracket per vertical profile. To simplify cost estimation, two brackets per square meter of panel can be considered.
Cost per area (Glass / cladding) To standardize the cost of the panel in this case, it can be treated as a unitized panel that may include, opaque panel, glass with an aluminium frame or solely glass, depending on the architectural design. For normalization, the calculation considers the panel as a single unit covering one square meter of facade area, allowing for a consistent cost estimation per square meter.

<u>Normalize number of layers in the stick system </u>(Per square meter)

- Frames – horizontal -2, vertical -2
- Fixed Frames – horizontal -2/2, vertical -2/2
- Bracket – 2
- Glass – 1 (per square meter)
- Frames – horizontal -2, vertical -2(unitized for glass) (figure kk)

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Lm, Lt, : Cost of stick frame (per Lengths in meters) of mullions, transoms
Lum, Lut, : Cost of unitized frame (per Lengths in meters) of mullions, transoms
Ai, Ag, Ac : Cost (per square meter area) insulation, glass, and cladding.
Ub : Cost (per Unit) Bracket.

Total cost = $(2\times Lm) + (2\times Lt) + (2\times Lum) + (2\times Lut) + (2\times Ag) + (2\times Ub)$

Estimation -Rear ventilated System layers

As shown in Figure 21, in a Rear-Ventilated Facade (RVF), the bracket system depends entirely on the construction detailing of the panels. For instance, if the panel design includes sheet panels, two brackets are typically required per panel at the top of the frame, where the frame hooks into place. Alternatively, with an agraffe hooking system, two or more brackets may be needed, depending on the panel's size. These brackets support the panel, which hangs on horizontal profiles that are, in turn, fixed to the vertical subframe.

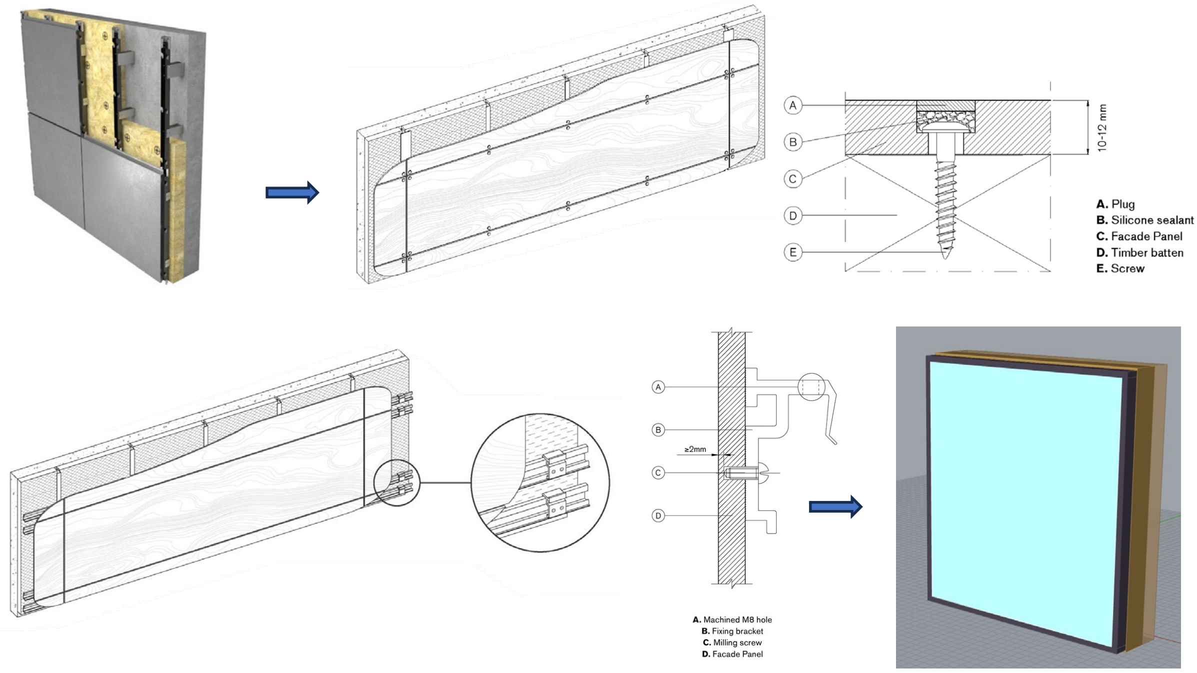

Figure 21 Option 1 bracket with vertical frame, Option 2 screw fixing system, Option 3 Hidden fixing with bracket hanging system, Semi unitized simplified.

Cost per length (Frame) The vertical and horizontal framing members form the substructure that supports the panels. To normalize the cost estimation for rear-ventilated (RVF) systems, we can consider two vertical and two horizontal frames per square meter of the facade. This approach simplifies the calculation and provides a consistent basis for estimating the framing costs across different facade areas.

Cost per item (Bracket) The brackets in an RVF system depend on the panel construction. For example, if the panels use sheet construction, each panel generally requires two brackets at the top to attach to the supporting frame. If an agraffe hooking mechanism is used, the number of brackets depends on the panel size, often requiring two or more to

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secure the panel to the horizontal profiles, which are then fixed to the vertical subframe. To simplify cost estimation, four brackets per square meter of panel can be considered.
Cost per area (For Glass and cladding)- The glass or cladding panels in an RVF system can be calculated based on their material costs per square meter. as they cover the visible surface area of the building.

Normalize number of layers in the stick system (Per square meter)

- Frames – horizontal -2, vertical -2
- Bracket – 4 (Figure NN.)
- Insulation – 1 (per square meter)
- Cladding – 1 (per square meter)

Lm, Lt, : Cost (per Lengths in meters) of mullions, transoms
Ai, Ag, Ac : Cost (per square meter area) insulation, glass, and cladding.
Ub : Cost (per Unit) Bracket.

Total cost = (2×Lm) + (2×Lt) +(2× Ai) +(2× Ag) +(2× Ac) + (4× Ub)

5. Cost normalization for all system

Total normalize cost of the facade = (Number of frames *(Cost per unit length of mullion + Cost per unit length of Transom)) + Cost per unit *(Number of the bracket per mullion) + (Cost per square meter area of the cladding) + (Cost per square meter area of the glass) + (Cost per square meter Membrane) + (Cost per square meter insulation)

The calculation method provided above can be applied to all facade systems based on the layers involved and the quantities specified in the architectural visualization. This normalized formula provides an approximate material cost for the facade, excluding fabrication and installation expenses. It serves as a basis for analysing the cost implications on the design, enabling optimization in terms of both cost efficiency and sustainability.

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5 Multi-criteria Design Approach for Multi-hazard and Low-carbon Facades and Components

5.1 Multi-Criteria Decision Making Procedure

Multi-Criteria Decision-Making (MCDM) provides a structured approach for solving problems with multiple conflicting criteria. Within MCDM, Multi-Attribute Decision Making (MADM) and Multi-Objective Decision Making (MODM) serve different purposes: MADM handles selection and ranking of discrete alternatives, while MODM focuses on optimizing objectives within a continuous solution space. In facade engineering, MADM is effective for evaluating predefined facade solutions and selecting the optimal choice, whereas MODM is appropriate for the optimization of design parameters [38]. For the assessment scope of Work Package 5, which involved the system-level selection of facade solutions, MADM is the more suitable approach. MODM can then be applied later to optimize the design of the selected system.

Given the varying nature of criteria, Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS) is deemed suitable, as it identifies the solution closest to the ideal point while maintaining a balance among criteria.

Step 1: Construct a decision matrix
Each row in Table 9 represents a potential facade system solution, and each column represents a criterion. For example:

Table 9 Decision matrix for multi-criteria analysis.

Facade System	Social Resilience	Technical Resilience	Environmental	Economic
S1	0.04	0.03	350	200,000
S2	0.01	0.04	300	250,000
S3	0.05	0.02	400	180,000
S4	0.07	0.05	250	220,000

Step 2: Normalize criteria values
Normalize each criterion to make them dimensionless and comparable. Values are normalized relative to the cap, the maximum value that determines the failure state or the performance limit of a facade system.
For each criterion j of facade system i, the normalized value N_{ij} is calculated as follows:

$$\mathrm{N}_{ij} = \left\{ \begin{matrix} \frac{\mathrm{X}_{ij}}{\mathrm{C}_j} & \text{if } \mathrm{X}_{ij} \leq \mathrm{C}_\mathrm{j} \\ 1 & \text{if } \mathrm{X}_{ij} > \mathrm{C}_\mathrm{j} \end{matrix} \right\}$$

Where:

- X_{ij} is the value of criterion j for facade system i

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- C_j is the capping threshold for criterion j

Examples of capping thresholds (C_j):
- $C_{resilience\ loss}$ = MAFE limit
- $C_{sustainability}$ = benchmark, regulatory level
- C_{cost} = budget limit

Step 3: Define the ideal solutions

This step establishes the prioritized criteria, resulting in different solution types: resilience-driven, carbon-driven, or cost-driven.

For example, in a resilience-driven solution:
- Ideal Solution (A+): The resilience criterion receives the highest weight and the ideal corresponds to the minimum value. For the secondary criteria (environmental and economic), equal weights are assigned.
- Negative Ideal Solution (A-): This is the worst-case scenario, corresponding to the maximum values for all criteria.

Step 4: Calculate the Euclidean Distance to Ideal and Negative Ideal Solutions

For each facade system, calculate the Euclidean distance to the ideal and negative ideal solution using:

$$D_i^+ = \sqrt{\sum_{j=1}^{n} \left(\text{Normalized Value}_{ij} - \text{Ideal Value}_j\right)^2}$$

$$D_i^- = \sqrt{\sum_{j=1}^{n} \left(\text{Normalized Value}_{ij} - Negative\ \text{Ideal Value}_j\right)^2}$$

Where:
- $Normalized\ Value_{ij}$ is the normalized value of facade system i for criterion j
- $Ideal\ Value_j$ represents the best performance
- $Negative\ Ideal\ Value_j$ represents the worst performance

Step 5: Ranking the Facade Systems

Calculate the relative closeness C_i for each facade system to the ideal solution:

$$C_i = \frac{D_i^-}{D_i^- + D_i^+}$$

Where:
- D_i^+ is the Euclidean distance to the ideal solution
- D_i^- is the Euclidean distance to the negative ideal solution

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5.2 Digitalization and Database Integration of MCDM Results

Digital representations of chosen facade system designs together with their assessment indicator metrics described in Section 3 and Section 4 are stored in a database system. The database contents are accessible to stakeholders through a web-based dashboard application.

The integration of assessment results into an interactive dashboard provides an accessible method for exploring and utilizing facade design data. Dashboard visualizes real-time rendered 3D models of facade elements, offering an intuitive interface for stakeholders. Each model is further enriched with performance indicators derived from the assessment framework, enabling users to quickly grasp the technical, organizational, social, and economic performance of each design. By aggregating all information in this manner, the dashboard ensures that users can identify facade systems that address specific hazards relevant to their building project.

Besides just database access, the dashboard enables advanced filtering capabilities, allowing users to explore designs based on chosen performance criteria. Once a suitable design is identified, users can extract additional design data for further analysis or integration into their own design workflows. By coupling data accessibility with performance-driven insights the dashboard supports informed decision-making in the pursuit of more resilient and sustainable facade systems.

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6 Conclusion

The deliverable 5.1 presented the multi-criteria framework for the design of resilient facades and components. It highlighted two aspect of resilience assessment: social resilience in relation to heat hazards and technical resilience in relation to damage-related hazards.

The framework includes: (1) methods and definition of scope in typologies; (2) decision making criteria; (2) framework for the quantification; (4) description of the multi-criteria approach to be used for decision making.

The framework here described is the basis for the deliverable 5.2, which will showcase a catalogue of solutions according to the criteria and approaches presented in this deliverable.

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