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Building envelope design in adaptive reuse: a comparative method proposal as support for designer’s technological choices

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Abstract

Environmental sustainability in the construction sector is an increasingly important issue. Façade is a part of a building's architecture that can play a significant role in improving energy efficiency and overall sustainability. This thesis aims to evaluate different façade renovation solutions, with a focus on dry façade systems, to determine which approach contributes the most to the enhancement of sustainability. An integrated design process was employed to address the research question, combining technical and non-technical criteria to assess the performance of various façade alternatives. In this regard, a multicriteria system-based tool, the Analytic Hierarchy Process (AHP), was utilized to classify and select the best solution. The tool was applied to two case studies having opposite features, both situated in Turin, Italy. The results of the analysis ranked the alternatives and showed how the ETICS is most suitable option. This approach wants to provide a decision-making instrument for a designer involved in building renovation projects and to serve as/deliver a framework to for further research and development.

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Abbreviations/Acronyms

AHP	Analytic Hierarchy Process
ANP	Analytic Network Process
BoQ	Bill of Quantity
CPD	Construction Products Directive
DSF	Double Skin Facade
EAD	European Assessment Document
EAE	European Association for ETICS
EBC	Energy in Building and Community
EC	European Commission
ECBCS	Energy Conservation for Building and Community System
ECSO	European Construction Sector Observatory
EIFS	External Insulation and Finish System
ELECTRE	Elimination Et Choix Traduisant la Realité
EOTA	European Organization for Technical Approval
EPS	Expanded Polystyrene
ERs	Essential Requirements
ETA	European Technical Assessment
ETAG	Guideline for European Technical Approval
ETICS	External Thermal Insulation Composite System
EVAMIX	Evaluation of Mixed data
GEA	Global Energiesprong Alliance
GFRC	Glass Fiber Reinforced Concrete
HPL	High Pressure Laminate
HVAC	Heating, Ventilation and Air Conditioning
IBP	Institute for Building Physics
IEA	International Energy Agency
LoR	Level of Recycling
MADA	Multi-Attribute Decision Analysis
MCA	Multi-Criteria Analysis
MCD	Multi-Criteria Decision making
MCDA	Multi-Criteria Decision Analysis
MW	Mineral Wool
NZE	Net Zero Emissions
NZEB	Nearly-Zero Energy Building
NWE	North-West Europe
PROMETHEE	Preference Ranking Organization Method for Enrichment Evaluation
PU	Polyurethane
PV	Photovoltaic
R&D	Research & Development
RQ	Research Question
TBA	Technical Assessment Body
UNI/TR	*Ente Nazionale Italiano di Unificazione*/Technical Report
UV	Ultraviolet
XPS	Extruded Polystyrene

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1. INTRODUCTION

Building renovation is a strategy for enhancing the sustainability of the built environment. According to the existing literature, the building industry is responsible for up to 40% of the final total energy consumption, split into 27% for residential and 13% for nonresidential, and 35% of associated carbon dioxide (CO_2) emissions, 20% for residential and 15% for nonresidential (Yang, Yan, & Lam, 2014). By engaging in such practices, the building construction sector not only consumes an immense amount of energy, but also causes significant harm to the environment. The extraction and processing of raw materials, the energy-intensive manufacturing processes, and the construction activities themselves all contribute to this substantial energy consumption. Moreover, these activities lead to the depletion of natural resources, habitat destruction, and increased pollution levels, which in turn contribute to environmental degradation. Consequently, the sector's operations have far-reaching negative impacts, extending beyond just energy consumption to include the destruction of ecosystems and biodiversity. These critical issues have spurred considerable efforts across various sectors of the construction industry to enhance the sustainability of buildings (Sadineni, Madala, & Boehm, 2011).

In this regard, the façade is the building's largest component and significantly contributes to the sustainability performance of the building as a whole; it is demonstrated that the total construction cost is influenced by the external envelope, accounting for between 25% and 40% (Kragh, 2011). Features like urban landscape and city image are attributed to the crucial role that façade plays, as it is constantly visible to the public and defines the character of buildings, towns, and cities. As the global focus on energy efficiency, environmental impact, and social well-being intensifies, the need for comprehensive façade renovation solutions has become increasingly important.

This thesis aims to evaluate different façade systems, with a particular emphasis on dry façade solutions, to determine which approach best contributes to the enhancement of sustainability. The primary research question (RQ) guiding this study is: "What type of dry façade system in the reuse of the building envelope contributes the most to the enhancement of sustainability?". To address this, an integrated design process was employed, combining technical and non-technical criteria to assess the performance of various façade alternatives. The criteria were identified through an extensive literature review in the fields of architecture, engineering, and construction. The criteria considered in this evaluation include construction cost, maintainability, sustainable resource use, recycling potential, aesthetic appeal, suitability to location, structural impact, installation time, and labour requirements. By incorporating these diverse factors, the goal is to provide a holistic framework for decision-makers involved in building renovation projects. The Analytic Hierarchy Process (AHP), a well-established multi-criteria decision-making (MCD) technique, was utilized to assign weights to the criteria based on their relative importance and reach the answers to the research question. This approach involved consulting a committee of professionals, also called stakeholders, who provided their input on the pairwise comparisons of the criteria through an interview. The use of MCD methods allows for a more objective and comprehensive evaluation of the façade alternatives, considering both quantitative and qualitative aspects.

Three main dry systems were selected for analysis in this study: External Thermal Insulation Composite System (ETICS), Rear Ventilated Façades, and Prefabricated Façades. Each system was examined in detail, considering its stratigraphy, benefits, drawbacks, and potential for enhancing sustainability. The results of the AHP analysis were then used to rank the alternatives and identify the most sustainable solution for the two different case studies. By employing an integrated design process and a multi-criteria analysis approach, this thesis aims to provide a valuable decision-making tool for architects, engineers, and project managers involved in building renovation projects. The findings contribute to the understanding of how dry façade systems can be optimized for sustainability, considering both technical and non-technical factors. The research also highlights the importance of stakeholder engagement and the need for a holistic approach to design and renovation. The structure of this thesis is as follows: Chapter 2 provides a comprehensive literature review on the topic of building renovation and the role of facade systems in enhancing sustainability. Chapter 3 outlines the research methodology, including the AHP framework and the criteria selection process. Chapter 4 presents the description of the case studies, while Chapter 5 discusses the methodology adopted for running the analysis. Chapter 6 provides analysis results and finally, Chapter 7 concludes the thesis with a summary of the key findings, implications, and recommendations for future research.

2. FAÇADE RENOVATION SYSTEMS

When considering façade renovation systems, three prominent approaches stand out: External Thermal Insulation Composite System (ETICS), Rear Ventilated Façade, and Prefabricated Façade. It can be said that they all take part in the renovation methods of dried construction, which means not using water in the execution of construction projects. All of them provide effective thermal insulation to improve energy efficiency and interior comfort, a wide range of aesthetic options by using different cladding materials and designs is allowed, modern building standards for weather protection, fire safety and durability are met, and last but not least they can be installed over existing facades without complete demolition, reducing construction waste and costs.

It was decided to consider a module of a typical façade system with dimensions of 1-meter width and 3-meter height considering all the aspects mentioned in the next sections, and with particular attention to integrated design principles.

2.1. External Thermal Insulation Composite System (ETICS)

The term ETICS (External Thermal Insulation Composite Systems), also known as EIFS (Exterior Insulation and Finish Systems) following the international convention, are certified technical solutions, designed and installed based on the ETA-applicant's instructions.

The ETICS kit comprises a prefabricated insulation product bonded onto the wall, or mechanically fixed using anchors, profiles, special pieces, etc., or a combination of adhesive and mechanical fixings. The insulation product is faced with a rendering consisting of one or more layers (site applied), one of which contains a reinforcement. The rendering is applied directly to the insulating panels, without any air gap or disconnecting layer (EOTA, Guideline for European Technical Approval of External Thermal Insulation Composite Systems (ETICS) with rendering, 2013). ETICS satisfies the function of thermal insulation and protection against the influences of weather but is not responsible for making the external wall airtight. This is ensured by the wall structure itself, or employing construction measures.

The first application of the system dates back to the early 1960s in central Europe in the city of Berlin on a residential building, and thanks to the innovative execution of the foamed plastic boards and synthetic resin plasters in the insulation system, scientific investigations have been initiated from the Fraunhofer Institute for Building Physics (IBP). Due to the gradual importance of external wall insulation systems, multiple examinations have been conducted during the next decades (Künzel, Künzel, & Sedlbauer, 2006).

Later on, the European Organization for Technical Approval (EOTA) was briefed by the European Commission (EC) to establish and publish a standard European approval guideline in accordance with Article 11 of the Construction Products Directive (CPD). Guidelines set out the performance requirements for the use as external insulation of building walls, the verification methods used to examine the various aspects of performance, the assessment criteria used to judge the performance for the intended use, and the presumed conditions for the design and execution. Moreover, based on the type of substructure, there can be different kinds of European Technical Approval Guidelines.

ETAG 004 is one of the European Guidelines. It was established in 2000 with the last update in 2013, and deals with External Thermal Insulation Composite systems (ETICS) with rendering intended for use as external thermal insulation to the building walls, made of masonry (bricks, blocks, stones…) or concrete (cast on-site or as prefabricated panels). As of 2021, EAD (European Assessment Document) 040083-00-0404 replaces ETAG 004 used until then as the European Assessment Document for the European Technical Approval. It's worth to be noticed that, according to Cortexa, a durable and effective ETICS system must include among other things, the presence of ETA certification and CE marking. Nowadays, the latter is voluntary due to the absence of harmonized European standards and, consequently, the choice for obtaining the marking is left to the manufacturer.

Member States are required to assume that approved products are suitable for their intended use, ensuring they meet Essential Requirements (ERs) throughout an economically reasonable working life. This presumption is based on the proper design and construction of works, as well as the accurate attestation of product conformity with the ETA, which is released by a Technical Assessment Body (TBA) (EOTA, Guideline for European Technical Approval of External Thermal Insulation Composite Systems (ETICS) with rendering, 2013).

For what concerning the Italian reference, Application Manual for ETICS developed by Cortexa has been used as starting documentation for the writing of the standard UNI/TR 11715, published on June 2018, dealing with "Isolamenti termici per edilizia- progettazione e messa in opera dei sistemi isolanti termici per l'esterno (ETICS)".

The construction package of the external thermal insulation composite systems consists of three macro parts: an insulating material, a reinforcement layer, and a finishing layer (Häkkinen, 2012).

Going into detail, ETICS is a set of construction elements consisting of specified prefabricated components (Figure 1):

- **Substrate** (grey layer)
- **Adhesive** (1)
- **Thermal insulation product** (2)
- **Anchors** (3)
- **Base coat** (4)
- **Reinforcement** (5)
- **Key coat** (6)
- **Finishing coat** (white layer)

The Substrate is intended to be the existing wall either masonry or concrete under surface preparation and it's the base where the system is applied, for fixing the substrate and the entire package, an adhesive/adhesive bed is used which carries the loads involved in it. The most common thermal insulation materials are expanded polystyrene (EPS) and mineral wool (MW), although also other materials have been using as substitutions, such as polyurethane (PU) and extruded polystyrene (XPS); however, EPS and XPS are preferred in areas exposed to splashed water. The system's adhesion to the substrate is achieved through bounding anchors, mechanical fasteners, or both. The base layer consists of a mortar directly applied onto the insulation panel with a fiberglass reinforcement mesh embedded in it, improving the mechanical behaviour and durability of the entire system. A very thin coat aiming as surface preparation is placed before the finishing coat, which has a decorative function and contributes to the protection against the weathering since it is directly exposed to local environmental loads (EAE, 2011).

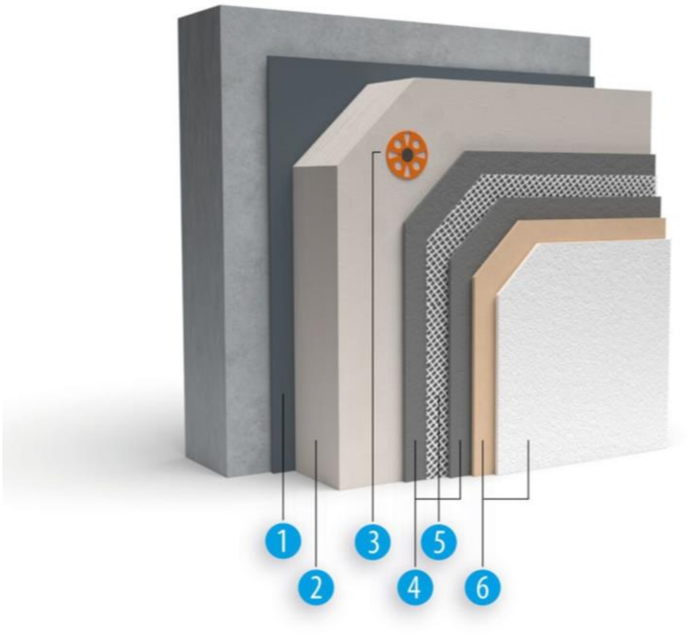


Figure 2.1.1 ETICS with rendering system (https://www.ea-etics.com/etics/about-etics/)

Looking at the design point of view, ETICS are differentiated according to the methods of fixing in order to transfer the embedded load into the substrate.

- **Bonded systems**
    - *Purely bonded ETICS*
      The load is totally distributed by the bonding layer. ETICS may be fully bonded over the entire surface or partially bonded in strips and/or dabs. The bonded area must be at least 20%.
    - *Bonded ETICS with supplementary mechanical fixings*
      The load is totally distributed by the bonding layer. The mechanical fixings are used primarily to provide stability and flatness of the outer face of the thermal insulation board until the adhesive has dried and has reached the final mechanical strength and acts as a temporary connection to avoid the risk of detachment. Supplementary mechanical fixing can also provide stability in case of fire. The bonded area must be at least 20%.
- **Mechanical fixed systems**
    - *Mechanical fixed ETICS with supplementary adhesive*

The load is distributed to the substrate by the mechanical fixings. The adhesive is used primarily to ensure the flatness of the installed system. The bonded area must be at least 20%.

- *Purely mechanical fixed ETICS*
  The load is totally distributed by mechanical fixings and the ETICS are secured to the wall by them only. The bonded area must be less than 20%.

The minimal bonded area S for bonded ETICS is calculated as follows:

$$S = \frac{(0.03\ x\ 100)}{B} \quad [\%]$$

Where:

- S = minimal bonded area, expressed in %
- B = minimal single failure resistance of the adhesive to the thermal insulation product in dry conditions for all the failure modes, expressed in kPa
- 30 = bond strength between adhesive and thermal insulation product in kPa corresponding to the minimal requirement on bonded ETICS

Taking this formula into account, the minimum bond strength lower than 30 kPa would lead to a bonded surface higher than 100%. Such an ETICS shall be mechanically fixed (EOTA, External Thermal Insulation Composite Systems (ETICS) with renderings, 2019).

The harmonization process on a European level is reached out by the implementation of the 6 Essential Requirements which apply to the construction works in question as a whole. The Essential Requirements rule the following areas:

- **Mechanical resistance and stability**
  Construction works must be designed and built to withstand loadings during construction and use in order not to lead to any of the following:
    - Collapse of whole or part of the work
    - Major deformations to an inadmissible degree
    - Damage to the other parts of the works or to fittings or installed equipment as a result of major deformation of the load-bearing construction
    - Damage by an event to an extent disproportionate to the original cause
- **Safety in case of fire**
  Construction works must be designed to ensure that in the event of a fire:
    - The load-bearing capacity of the construction can be assumed for a specified period
    - The generation and spread of fire and smoke within the works are limited
    - The spread of the fire to neighboring construction works is limited
    - Occupants can leave the works or be rescued by other means
    - The safety of rescue teams is taken into consideration

- **Hygiene, health and the environment**
  Construction work must be designed and constructed to ensure it does not pose a threat to the hygiene or health of occupants or neighbors. This includes preventing:
    - The giving-off of toxic gas
    - The presence of dangerous particles or gases in the air
    - The emission of dangerous radiation
    - Pollution or poisoning of the water or soil
    - Faulty elimination of wastewater, smoke, solid or liquid wastes
    - The presence of dampness in parts of the works or on surfaces within the works
- **Safety in use**
  Construction work must be designed and constructed to avoid the presence of unacceptable risks of accidents in service or operation such as slipping, falling, collision, burns, electrocution, and injury from explosion.
- **Protection against noise**
  Construction work must be designed and built in such a way that noise perceived by the occupants or people nearby is kept down to a level that will not threaten their health and will allow them to sleep, rest, and work in satisfactory conditions.
- **Energy economy and heat retention**
  The construction work and its heating, cooling, and ventilation installations must be designed and built in such a way that the amount of energy required in use shall be low, having regard to the climatic conditions of the location and the occupants (EAE, 2011).

ETICS allows the integration of the insulation performance by overlaying a new layer on the old system in a solution called "ETICS on ETICS". It is a specific system for the energy requalification and maintenance of existing thermal insulation systems which needs to satisfy specific conditions in order to guarantee the functionality of the ETICS that will lead to the choice of superimposition measures.

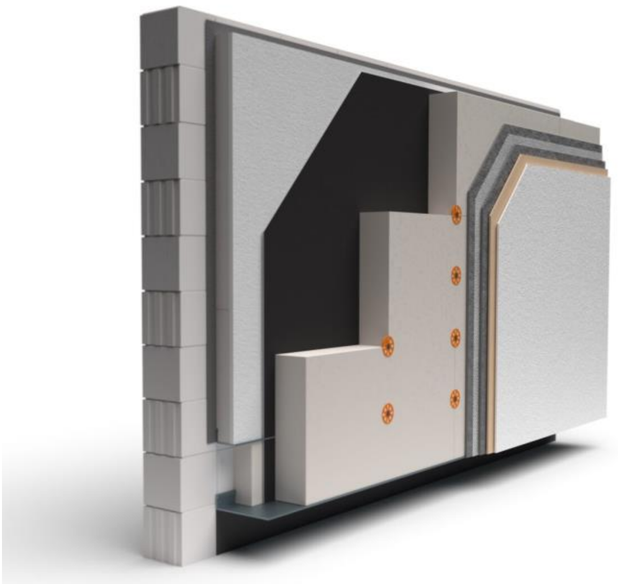


Figure 2.1.2 ETICS on ETICS (https://www.ea-etics.com/etics/about-etics/).

It can be applicable to:

- Systems with a stable, compact, and non-detached surface
- Systems composed of EPS sheet and mineral wool adhered to the wall, properly glued and dowelled (if applicable), and plastered wood fiber panels
- Systems without evidence of accidental moisture damages
- Systems lacking noticeable cracks or significant lesions

2.1.1. Benefits

External Thermal Insulation Composite Systems (ETICS) offer several benefits in building construction, providing enhanced thermal performance, durability, and aesthetics possibilities. Here they are listed:

- **Improved Thermal Performance**
  ETICS significantly enhance the thermal insulation of buildings, reducing heat transfer through exterior walls. By minimizing thermal bridging, ETICS contribute to more consistent indoor temperatures and lower energy consumption for heating and cooling.
- **Energy Efficiency**
  The improved thermal performance of ETICS leads to increased energy efficiency, resulting in reduced heating and cooling costs. Lower energy consumption contributed to environmental sustainability by reducing greenhouse gas emissions.
- **Aesthetic Versatility**
  ETICS can be applied to various building surfaces, offering a wide range of finishes, textures, and colors. This versatility allows architects and designers to achieve the desired aesthetic appearance, increasing the visual appeal of the building.
- **Durability and Weather Resistance**
  ETICS protect the building structure from weathering, including exposure to rain, wind, and UV radiation. The insulation materials and finishes are designed to resist degradation over time, contributing to the long-term durability of the building envelope.
- **Condensation Prevention**
  Properly installed ETICS help prevent condensation on interior surfaces, reducing the risk of mold growth, moisture-related issues, and damage to building components.
- **Versatility in Application**
  ETICS can be applied to both new construction projects and existing buildings, making them suitable for retrofitting and renovation projects. They are applicable to various types of vertical and, in some cases, horizontal surfaces.
- **Non-Intrusive Installation**
  Installation of ETICS is typically carried out on the exterior of the building, minimizing disruption to occupants during the construction process.

- **Reduced Thermal Bridges**
  ETICS help eliminate or minimize thermal bridges, which are areas of increased heat transfer that can compromise overall thermal efficiency.
- **Sound Insulation**
  The additional layer of insulation provided by ETICS can contribute to improved sound insulation, reducing the transmission of external noise into the building.
- **Compliant with Building Codes**
  Using ETICS that comply with relevant building codes and standards helps ensure that the construction meets regulatory requirements for energy efficiency and safety.
- **Fire Resistance (in some cases)**
  Certain ETICS systems are designed with fire-resistant materials, contributing to high fire safety in buildings.

It is important to note that the specific benefits can depend on factors such as the quality of materials, proper installation, and adherence to local building regulations.

2.1.2. Drawbacks

The systems provide also potential drawbacks and challenges associated with their use. Here are detailed considerations regarding the disbenefits of ETICS:

- **Initial Cost**
  The upfront cost of installing ETICS can be relatively high, including materials, labor, and potential specialized expertise for installation. This can be a significant consideration, particularly for budget-conscious projects.
- **Maintenance Requirements**
  Depending on the chosen finishes and environmental conditions, some ETICS may require periodic maintenance to preserve their appearance and functionality. This maintenance can involve cleaning, repairs, or even recoating, adding to the overall cost of ownership.
- **Installation Complexity**
  Proper installation of ETICS requires careful planning and execution. Any errors in the installation process can compromise the system's effectiveness and durability. Specialized knowledge and skills may be necessary, increasing the complexity of the construction process.
- **Moisture Management**
  Improper installation or damage to the system could lead to moisture-related issues, such as water infiltration behind the insulation. If not addressed promptly, this can result in damage to the building structure and reduce the insulation's effectiveness.
- **Fire Resistance**
  While some ETICS are designed to be fire-resistant, it's crucial to select systems that comply with local fire safety regulations. In some cases, additional fire protection measures may be necessary, adding complexity and cost.

- **Aesthetic Changes**
  The application of ETICS can change the appearance of the building exterior. This may be a disadvantage if the goal is to maintain a specific architectural style, especially in historical or aesthetically sensitive areas.
- **Weight Considerations**
  The additional weight of the insulation and finishing layers may require structural assessment, especially in older buildings. This assessment may lead to additional costs and considerations during the planning phase.
- **Long-Term Durability Concerns**
  The long-term durability of ETICS may depend on factors such as the quality of materials, installation, and ongoing maintenance. In some cases, premature deterioration or failure may occur, and repair costs will be needed.
- **Compatibility Issues**
  Ensuring compatibility with existing building components or features can be a challenge, especially in retrofit projects. Compatibility issues may require additional modifications or adjustments, adding complexity to the installation process.
- **Potential for Misuse**
  Inappropriate or unregulated use of ETICS, including substandard materials or improper installation, can lead to inefficiencies, reduced effectiveness, and safety concerns.
- **Regulatory Compliance**
  Compliance with local building codes and regulations is essential. Failure to meet these standards may result in costly corrections or even legal consequences.

2.1.3. Stratigraphy of a Façade Module Sample

A typical façade module of ETICS solution is:

Solution A1	
No.	**Component**
1	Existing wall
2	Adhesive
3	Mineral Wool
4	Screw anchor
5	- Mortar with fiberglass reinforcement mesh - Fixing agent - Silicone finishing

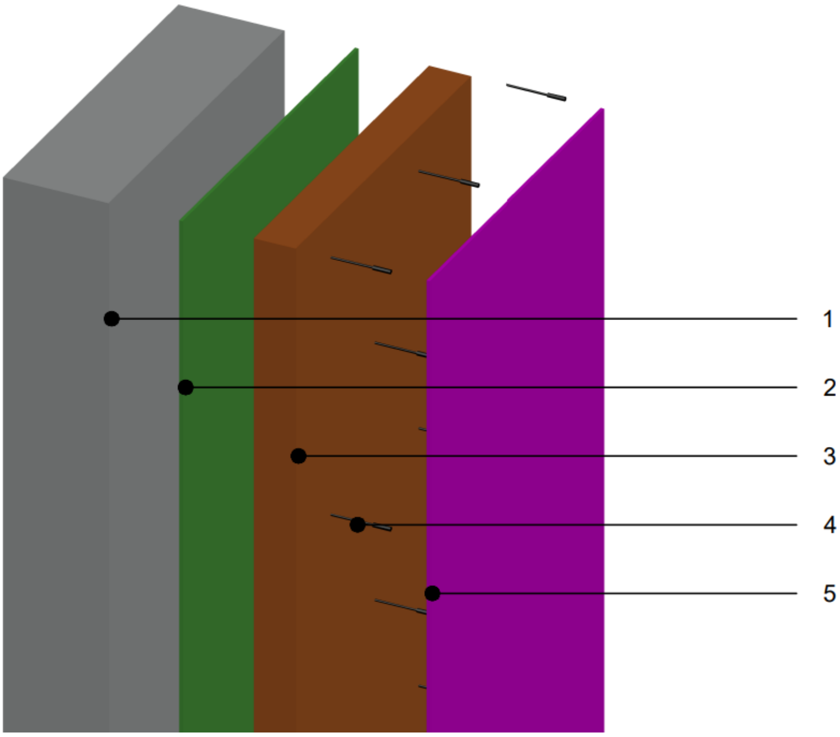


Figure 2.1.3 ETICS stratigraphy (by the author).

2.2. Rear Ventilated Façade

The concept of a rear "ventilated façade", also known as a "ventilated façade" or "rain-screen façade", has evolved over time and has its roots in both architectural and engineering practices. The idea of ventilated facades has historical roots in traditional building practices where gaps or voids were intentionally left in building envelopes to allow for natural ventilation and moisture control. The concept gained attention as architects and builders sought ways to improve building performance, especially in the context of moisture management and thermal comfort.

The origins of the ventilated façade came from the concept of double skin façade (DSF) proposed for the first time by the Swiss-French architect Le Corbusier in the early 1900s. His "Mur neutralisant" was a significant element within a broad array of innovative concepts aimed at incorporating artificial climate control systems into architectural elements. This invention served as an early model for a double skin façade, featuring an integrated air-conditioning circuit designed to enhance both comfort and energy efficiency through optimized insulation. While the system was envisioned to be adaptable to various materials, it was the iteration featuring a double skin glass façade that played a crucial role in supporting one of his key design elements "the glass curtain wall" known as "le pan de verre." (Gutiérrez, 2012)

The entry of cold can take away the necessary comfort in the vicinity of the glazing. A technical obstacle, a technical answer: simply double the glazed area that makes up the façade, with a second pane of glass located 5 or 10 cm from the first, and circulate a non-breathable warm air current produced in a small heating system in this cavity. This is what I have called a "Mur neutralisant" (Neutralising wall).-Le Corbusier,1933

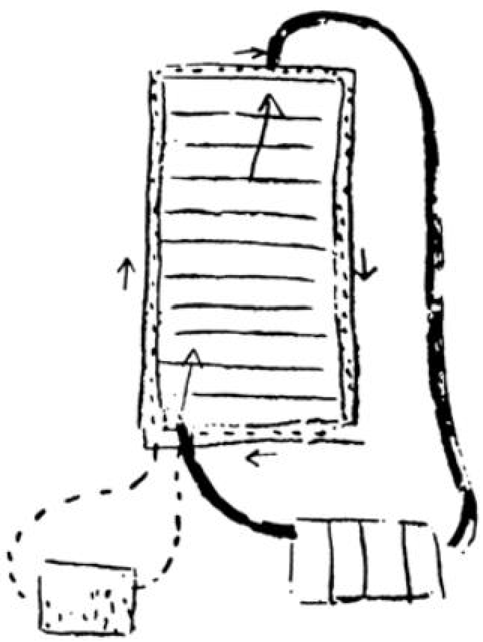


Figure 2.2.1 Mur Neutralisant (by Le Corbusier).

Over the years, simple but efficient rain-screen wall solutions have been adopted both in Alpine and Northern European countries, aiming to protect the external partition of those rural and mountain buildings from the external precipitations, typical issues faced in that environment (Ibáñez-Puy & Marina Vidaurre-Arbizu, 2017).

Nowadays, the ventilated façade system is ruled by the standard ETAG 034-1 which specifies the requirements each individual component of the system must satisfy. This guideline covers kits for vertical exterior wall claddings consisting of an external cladding, mechanically fastened to a framework (specific to the kit or not), which is fixed to the external wall of new or existing buildings (retrofit). An insulation layer is usually fixed on the external wall (EOTA, Guideline for European Technical Approval of kits for external wall claddings Part I, 2012). The Italian reference standard UNI 11018 describes ventilated façade as: "a type of façade with advanced screen in which the cavity between the cladding and the wall is designed so that the air present in it can flow by chimney effect in a natural and/or artificially controlled way, according to seasonal and/or daily requirements, in order to improve its overall thermal energy performance".

The term "ventilated wall" is outside wall cladding application composed of an insulation layer directly applied to the existing wall with an external covering made up of elements of various types, varying in size and material consistency. These elements are characterized by dry installation, using mechanical or chemical-mechanical suspension and fixing devices, which keep the side hidden from the backing wall separated. The system creates a ventilation zone between the thermal insulation and cladding materials which is in contact with the atmosphere. This cavity allows the circulation of the external air and constitutes an air chamber within which natural ventilation is generated due to the so-called "chimney effect" phenomena. The air gap must be thick enough to interrupt the physical continuity between the external covering and the other components forming the internal core of the facade wall. From the standard ETAG 034-1 it needs to be at least 20mm, whereas literature sources specify dimensions in the range of 20-50mm (TC, 2003) (Sanjuan, Suárez, González, Pistono, & Blanco, 2011), some other sources have quite higher values in between 40 and 100mm (Ibáñez-Puy & Marina Vidaurre-Arbizu, 2017).

On the other hand, the dimension of the ventilation space is not the only parameter influencing the air flow rate through the cavity. The number of ventilation slots plays a pivotal role in regulating the flow, and for what just said, ventilated façades are distinguished into two types:

- **Open-joint ventilated façade**
  Ventilated facades featuring open joints enable unobstructed airflow between the cavity and the external environment via the gaps formed by the components composing the outer layer. The ascending movement of the air is activated by the temperature gradient between the inward and the outward temperatures, and the air flow rate is commanded by the grills' size.
- **Closed-joint ventilated façade (opaque ventilated façade)**
  A ventilated façade with closed joints is lacking of joints between pieces that make up the outer skin, and for this reason air circulation is possible due to the existence of some openings at the bottom and the top of the cladding, considerably decreasing the air flow rate (Cascone & Lionti, 2017) (Astorqui & Porras-Amores, 2017).

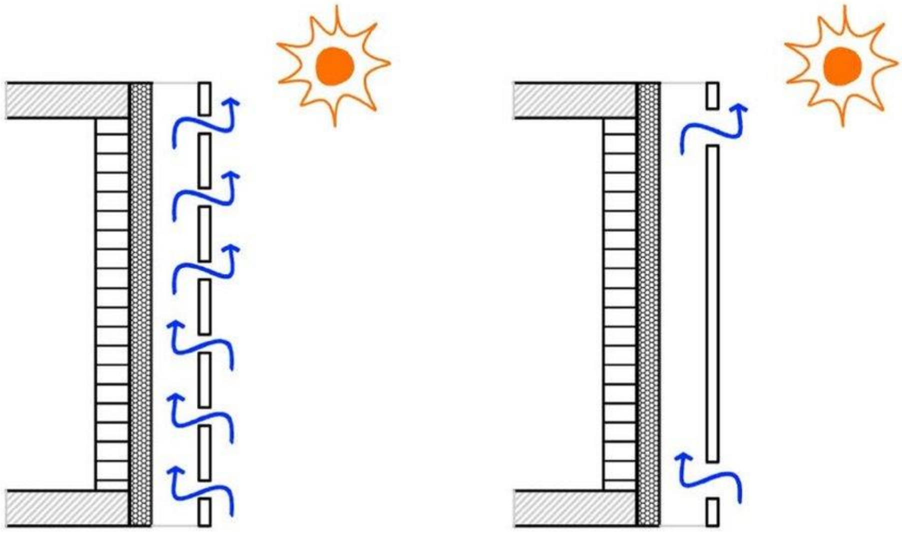


Figure 2.2.2 Open-joint (left) and Closed-joint ventilated façade (Ibáñez-Puy & Marina Vidaurre-Arbizu, 2017).

A ventilated façade can be schematized as it follows:

- **Base material** (1)
- **Bracket fasteners** (2)
- **Insulation** (3)
- **Insulation fastener** (4)
- **Bracket/profile** (5)
- **Profile fasteners** (6)
- **Cladding material** (7)
- **Cladding fastener** (8)

The base material to which the façade can be anchored may be made up of standardized materials (e.g. concrete, brick, steel, timber, etc.) or non-standardized materials. The bracket fasteners, as well as the profile and the cladding ones, must comply with national and/or European regulations. Bracket ones are used to anchor substructures to load-bearing base materials thanks to three main methods: anchor fastening on brick and concrete, screw fastening on timber or steel, and direct fastening on concrete. Panels of thermal insulation material suitable for the intended purpose must be carefully inserted and placed one next to each other avoiding insulation discontinuity. They can be differentiated among mineral wool, foam glass, rigid foam sheet and wood fiber board. Anchor bolts are used for mounting the insulation panels without gaps ensuring the continuity among them. The bolt's length is chosen in compliance with the thickness of the thermal layer for penetrating sufficiently into the base material. The brackets/profile, including the fasteners, form the substructure of the façade which is the static link between the load-bearing outer wall and the façade cladding. The laying pattern is defined on the basis of the finishing elements' modularity and the structural loads involved. Profile fasteners are the components that connect the different parts of the substructure in a mechanical way. The cladding modules used (made of tiles, stone, ceramic, wood, metal, etc.) are fixed either to a secondary structure of metal cross pieces or to special anchoring plates fixed directly on the uprights. Material that is fixed to the substructure by way of rivets, screws, undercut anchors, and adhesive bonding.

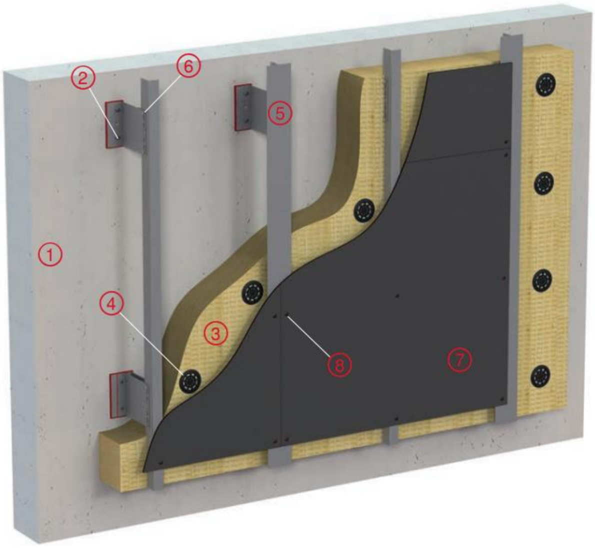


Figure 2.2.3 Ventilated façade scheme
(https://www.hilti.co.uk/content/hilti/E1/GB/en/business/business/engineering/ventilated-facade.html).

Ventilated façade cladding can be realized with elements of various shapes and dimensions and with a wide list of different materials. Cladding generally consists of panels, thin slabs, or hollow three-dimensional element, based on the type of material adopted. The most common ones are (HILTI):

- **Fiber-cement:**
  Composite material made of sand, cement, and cellulose.
- **High-Pressure-Laminate (HPL):**
  It's composed of resin impregnated paper layers, a decorative paper layer and a clear melamine overlay. These sheets are bonded at high pressure and temperature.
- **Metal:**
  Materials such as aluminum, stainless steel, copper, or steel are obtained starting from thin metal sheets.
- **Render:**
  Cement board, on which a layer of render is applied.
- **Ceramic:**
  Natural materials like quartz, granite, and clay.
- **Terracotta:**
  A clay-based unglazed or glazed ceramic cladding material.
- **Stone**
- **Composite:**
  Formed by two aluminum layers and a mineral or plastic core.

2.2.2. Benefits

Ventilated façades offer a wide range of benefits that contribute to the overall performance, energy efficiency, and aesthetics of a building. Here are some additional details about the advantages of ventilated façades:

- **Hygrothermal Performance**
  Ventilated façades effectively manage moisture, preventing condensation within the building envelope. This is crucial for avoiding issues like mold growth, which can compromise indoor air quality and the structural integrity of the building.
- **Thermal Inertia**
  The air gap in ventilated façades provides thermal inertia, helping to slow down the transfer of heat. This contributes to a more stable indoor temperature, reducing the need for frequent heating or cooling adjustments.
- **Energy Savings**
  The insulation provided by the air gap and cladding materials helps in maintaining a consistent indoor temperature. This leads to energy savings as the building requires less energy for heating and cooling throughout the year.
- **Rain Screen Effect**
  Ventilated façades function as a rain screen, preventing direct contact between rainwater and the building structure. This reduces the risk of water infiltration and protects the underlying structure from water-related damage.
- **Customization and Architectural Detailing**
  The design versatility of ventilated façades allows for intricate architectural detailing. Architects can incorporate features such as recessed panels, varied textures, and creative patterns, adding aesthetic value to the building.
- **Material Longevity**
  The protective layer created by the ventilated façade shields the building materials from harsh environmental conditions, UV radiation, and pollutants. This protection enhances the longevity of both the façade materials and the overall building structure.
- **Air Circulation and Ventilation**
  The air cavity in ventilated façades facilitates continuous air circulation. This natural ventilation helps in reducing indoor air pollutants, preventing stagnation, and creating a healthier indoor environment.
- **Integration with Renewable Energy Systems**
  Ventilated façades can be integrated with renewable energy systems, such as solar panels or solar thermal collectors. The façade’s design can accommodate these technologies, contributing to the building's overall sustainability.
- **Dynamic Façade Design**
  Ventilated façades allow for dynamic design possibilities, including the use of movable elements or shading devices. This adaptability enhances the façade’s performance in response to changing environmental conditions.
- **Ease of Installation and Maintenance**
  The modular nature of ventilated façades often simplifies the installation process. Additionally, the reduced maintenance requirements, such as the need for cleaning and repairs, contribute to cost-effectiveness over the building's lifecycle.
- **Acoustic Benefits**
  The air gap in ventilated façades provides an additional layer that contributes to sound insulation. This is especially beneficial in urban environments, reducing the impact of external noise on the interior spaces.

- **Fire Resistance**
  Depending on the cladding materials chosen, ventilated façades can offer good fire resistance. Certain materials used in ventilated facades may have inherent fire-retardant properties, enhancing the overall safety of the building.

2.2.3. Drawbacks

In the planning and implementation of a ventilated façade system, it is essential to consider also disadvantages:

- **Cost**
  The higher initial cost of ventilated façades includes expenses for additional support structures, air gaps, and specialized materials. This cost can be a significant factor in the decision-making process, especially for budget-conscious projects.
- **Installation Complexity**
  The installation of ventilated façades involves multiple components and can be complex. Achieving precision in alignment, ensuring proper ventilation, and managing load distribution can be intricate and require skilled labor.
- **Maintenance Accessibility**
  While ventilated façades generally require less maintenance, addressing issues within the air gap or behind the cladding may necessitate specialized equipment or extensive disassembly, making regular inspections more challenging.
- **Structural Load Considerations**
  The added weight of the ventilated façade system needs careful consideration, especially in retrofitting or when applied to existing structures. Structural assessments and reinforcements may be required to accommodate the additional load.
- **Insulation Challenges**
  The effectiveness of the insulation provided by the air gap may be compromised in certain configurations. Factors such as the width of the air gap, choice of insulation materials, and overall design influence the thermal performance.
- **Renovation Challenges**
  Retrofitting existing buildings with ventilated façades can be complex due to the need for structural modifications and the potential impact on the building's aesthetics. The feasibility of such renovations depends on the existing structure and design.
- **Design Constraints**
  Some architectural designs may not easily integrate with the requirements of a ventilated façade system. Design constraints can limit the options for incorporating an air gap or specific cladding materials.
- **Water Ingress Risk**
  While ventilated façades aim to prevent water infiltration, issues such as driving rain, inadequate detailing, or maintenance lapses can potentially lead to water ingress into the air gap, posing a risk of damage to the building structure.

- **Fire Safety Challenges**
  The choice of cladding materials plays a crucial role in fire safety. Certain materials may not be inherently fire-resistant, and if not properly treated or installed, they could contribute to the spread of fire. Meeting fire safety regulations becomes essential.
- **Extended Installation Time**
  The intricate nature of ventilated façade systems can result in a longer installation time compared to simpler façade solutions. This extended construction schedule may impact project timelines.
- **Limited Soundproofing in Some Cases**
  While ventilated façades contribute to sound insulation, the degree of soundproofing may not match that of specialized acoustic solutions. In noise-sensitive environments, additional measures may be needed.

2.2.4. Stratigraphy of a Façade Module Sample

A typical façade module of ventilated façade solution is:

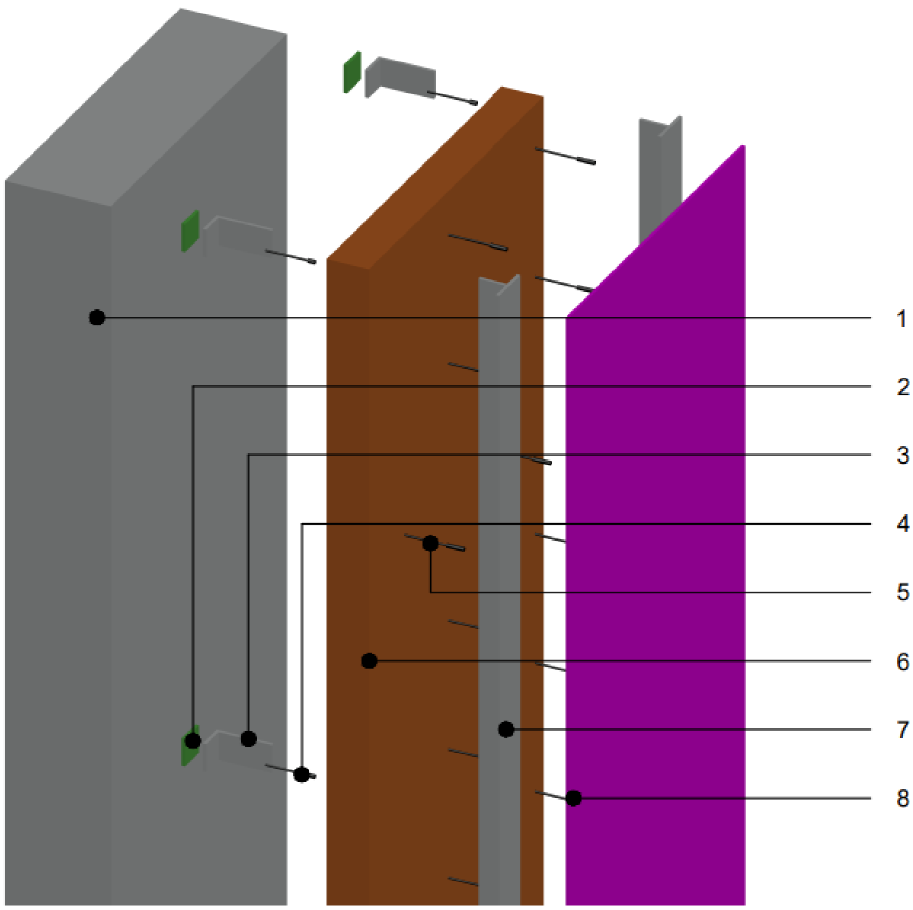


Figure 2.2.4 Ventilated façade stratigraphy (by the author).

Solution A2	
No.	**Component**
1	Existing wall
2	Neoprene layer
3	Aluminum bracket
4	Bracket fastener
5	Screw anchor
6	Mineral wool
7	Structural mullion
8	PV panel

2.3. Prefabricated Façade

Prefabricated façades, also known as modular or panelized façades, have roots in the broader history of prefabrication and industrialization in construction. The prefabricated architecture began to take part in the need to build on sites that were unsuitable for construction and difficult to access. It involves designing and constructing building components separately, often in different locations, and assembling them on-site; an approach that emerged from emergency situations, colonizations, or settlements in new territories where traditional construction methods faced limitations. The development of prefabrication is also linked to socio-political scenarios that influenced mass construction plans, and its progress differed between North America and Europe due to varying socio-economic factors.

The western history of prefabrication traces back to Britain's global colonization efforts, with the first recorded case in 1624 involving houses shipped by boat from England to the fishing village of Cape Anne, in what is now a city of Massachusetts (Smith, 2010).

Over time, industrialization experiments sought to enhance prefabrication with materials like wood, steel, and iron, addressing questions about its impact on the built environment and the simultaneous improvement of design and production quality. In recent times, the motives behind prefabrication remain consistent: building in remote locations, reducing construction time, and achieving mass production; construction activities have been shifted from traditional on-site work to factories, where frames, modules, or panels are prefabricated. Buildings are seen as systems of components rather than finished products, and industrialized systems enable the reuse of standardized components, promoting efficiency and diversity within a coordinated framework.

The shift from prefabricating single building elements to adopting modular prefabrication went through an experimental phase in the 1920s. During this period, entire residential units were constructed, fully produced, and assembled in factories. The first experiments were conducted by the American engineer Richard Buckminster Fuller with his "Dymaxion house" (*__dy__namic, __max__imum, tens__ion__*) in 1928, and by the French designer Jean Prouvé with his "Case Meudon" in 1949 (Smith, 2010).

Prefabricated façade is used to refer to façades constructed by assembling components manufactured off-site, often in a controlled factory environment for reducing the actual erection time on-site, to form a cohesive façade consisting of wood, glass, metal, stone, or precast/GFRC (glass fiber reinforced concrete) cladding panels. These systems are intricate, featuring multiple layers and materials, with each layer serving specific functions such as protection from water, air infiltration, visibility, and thermal transmission. Once they arrive at the construction site, the prefabricated elements are either directly lifted by a crane on the substructure or attached to the armature, which is then connected to the substructure; erection takes place without scaffolding. Furthermore, the non-load-bearing enclosure systems include glass curtain wall, metal façade, precast cladding and masonry, with an increasing attention towards wood and polymer façades (Smith, 2010) (Herzog, Krippner, & Lang, 2004).

Figure 2.3.1 Mounting a prefabricated, highly insulating façade element.

In general, the adoption of prefabricated module systems can find place for both new construction projects and retrofit interventions. Their versatility and adaptability make them a valuable solution in various construction scenarios.

1.3.1. Retrofit Intervention – ENERGIESPRONG Project

The principal source of energy waste at the European level can be attributed to the building stock, equal to 40% of the entire waste (Programme, 2021). Within this percentage, the residential buildings represent the biggest quote and a subsequence differentiation of 64% due to single family buildings, and 36% to the apartment blocks. Only a small part of these has been gone under retrofit interventions (Economidou, et al., 2011). The use of this proposal put the basis for a holistic approach involving again the waste materials into the building's energy implementation, in coherence with sustainable development.

The International Energy Agency (IEA) was the first to face the global dialogue on energy security and clean energy transitions, being the world's leading energy authority. The IEA was established in 1974 in response to the need for the major energy consuming countries to co-operate effectively on a broad spectrum of energy policies and most urgently on security of oil supply. The fundamental changes in economics and politics regarding to the international oil market, during the period leading up to the Middle East War crisis of 1973-1974, may be laid the foundations to the origin of the Agency (Agency & Scott, 1994). Today energy security remains a central part of IEA mission, but it has a wider purpose focusing on a full range of energy issues, including climate change and decarbonization, energy access and efficiency, investment and innovation, and ensuring reliable, affordable, and sustainable energy systems ((IEA), From oil security to steering the world toward secure and sustainable energy transitions, 2024).

In 1977 the Agency established an Implementing Agreement on Energy in Building and Communities (EBC), formerly known as Energy Conservation for Building and Community Systems Programme (ECBCS). This area deals with the development and facilitation in the integration of technologies and processes for energy efficiency and conservation into healthy, low emission, and sustainable buildings and communities, through innovation and research. The programme offers a unique opportunity for researchers and experts supported by national programs and industry funding to collaborate and generate exceptional project outcomes. Furthermore, it leads not only to the creation of high-quality outputs, but also strengthens personal technical networks, providing lasting benefits in terms of knowledge exchange, professional relationships, and ongoing collaboration opportunities ((IEA), About Energy in Buildings and Communities (EBC), 2024).

The field of application of research and development strategies goes from residential, commercial, office buildings to community systems, influencing the building industry in three focus areas of R&D activities: dissemination, decision-making, building products, and systems. The management of the programme is ensured by an Executive Committee, which consists of controlling the existing projects on one side, and identifying new areas where collaborative effort may be beneficial on the other side ((IEA), Annex 50 - Prefabricated Systems for Low Energy Renovation of Residential Buildings, 2011).

The EBC carries out a series of projects known as “Annexes”, so called because they are legally established as annexes to the Implementing Agreement; in particular “Annex 50: Prefabricated Systems for Low Energy Renovation of Residential Buildings (2006-2011)” dictates the guidelines at the refurbishment intervention level.

The term “retrofitting” refers to the process of making modifications or additions to an existing structure or system to improve its performance, energy efficiency, safety, or compliance with current standards.

In architecture, retrofitting involves virtuous practices for regenerating existing building fabric, emphasizing sustainability in both energy and economic aspects. It goes beyond restoration and renovation, rethinking and redesigning properties to enhance market value and meet contemporary spatial and functional needs. Retrofitting is applicable at various scales, from individual buildings, improving systems such as HVAC, lighting, insulation, to urban neighborhoods, contributing to the redesign and revitalization of cities for the future.

It's worth noting that among the traditional methods of retrofitting, the Dutch one sticks out for its innovative program which combines practical and conceptual aspects.

Energiespong (in English Energy Leap) is a project born in Netherlands coordinated by the Global Energiesprong Alliance (GEA) and actuated for the first time in 2014 on an existing building intervention, which lasted 15 days only. In the early January, the project has been recognized with the prestigious 2024 Gold World Habitat Award for its innovative and financially sustainable approach to address climate change and improve energy efficiency in buildings (European Climate, 2024).

The aim of the method is to bring about desirable, viable net-zero energy refurbishment solutions to the mass market, in other words transforming the existing dwellings into net-zero energy houses. This can be translated into generating the exact amount of energy needed for heating, hot water, lighting, and all the electrical appliances present inside the building units. Furthermore, by achieving NZEB energy performance, Energiesprong stands out by delivering effective results while appealing to industry, housing providers, and residents. It utilizes an energy performance contract bringing fully integrated refurbishment packages and ensuring the long-term performance of improvements over a minimum 30-year period in order to provide financial security to property owners. Beginning with a 3D scan of the building, both inside and outside, a 3D model is produced, which stands as the starting point for a single retrofit plan bringing all NZE components together. The envelope solutions involve insulated wall cladding, with masonry veneer and windows, removal of internal windows, roof replacements complete with insulation and PV arrays. Insulation is installed underneath the homes where possible, new kitchens and bathrooms are provided with the installation of an energy unit so that generation of renewable energy is carried out on-site ((ECSO), 2017). Since the retrofit is non-intrusive, the residents do not need to move out during the requalification.

Facing the regulatory requirements that the model must comply with, there is no specific norm for this innovative system. However, the essential characteristics (performance) required for this system can be defined on the standard EAD 090062-00-0404 dealing with kits for external claddings mechanically fixed, on the premise of developing an envelope solution oriented towards the renovation sector. Likewise, the Energiesprong model can be applied in compliance with existing regulations and standards on energy efficiency and building renovation.

Unlike in Netherlands the program has taken off thanks to the government itself, which funded an association known as “Stroomversnelling” aimed to create NZE buildings on a large scale, in Italy this has not occurred (Alliance, s.d.). While the Dutch association attracts funding through European projects such as Transition Zero (Horizon 2020), E=0 (Interreg NWE), Mustbe0 (Interreg NWE), the Italian association “EDERA” is not receiving any money either from the Italian State or other European fundings, but from the partnerships with private companies. EDERA, short for Enabling Deep Regeneration, is a no-profit social enterprise, born in 2020 and financed by REDO SGR S.p.A. Società Benefit, FHS - Fondazione Housing Sociale, ANCE – Associazione Nazionale Costruttori Edili, and by Fondazione Cariplo (EDERA, 2024).

Besides the Energiesprong project mainly focuses on the residential portion and especially on single-family villas, in Italy the goal is to achieve interventions at a bigger scale, or educational buildings because they represent another consistent piece of structures that need to go under refurbishment.

The first application has been registered by a small project for home renovations for returning to an energy-neutral level: Parallelweg in Melick. The case study is formed by four residences that had several problematic aspects regarding the insulation of the whole external envelope, including high thermal transmittance due to single glass windows, and the heating systems served by an old boiler. As concerning the exterior walls, a package of prefabricated façade elements has been utilized, the so-called “StoTherm Classic”, which by means of a combination between the insulation layer and the reinforced plaster layer, impact-resistance and tear-resistance has been brought to the system. An individual air heat pump and a balanced ventilation, with a heat recovery unit, has been installed as well.

Figure 2.3.2 Parellelweg, Melick after renovation (https://www.energiesprong.uk/publications).

Energiesprong's radical transformation aims to establish a volume market for solutions that meet five key criteria:

1. Energy performance is guaranteed for 30 years. This can be achieved by the quality of the deep retrofit of the building focusing on high indoor climate and energy performance standards.
2. Hassle-free, one-week implementation. This criterion guarantees the not movement of residents during the intervention period.
3. Affordability. Reduced maintenance pays back the initial amount of money invested, resulting in energy cost savings and higher value of the property.
4. Attractiveness. Quality in the refurbishment makes energiesprong properties more attractive for both investors and residents.
5. From tendering to purchasing. The purchase of well-developed housing concepts is preferred, as the energy and indoor quality are guaranteed.

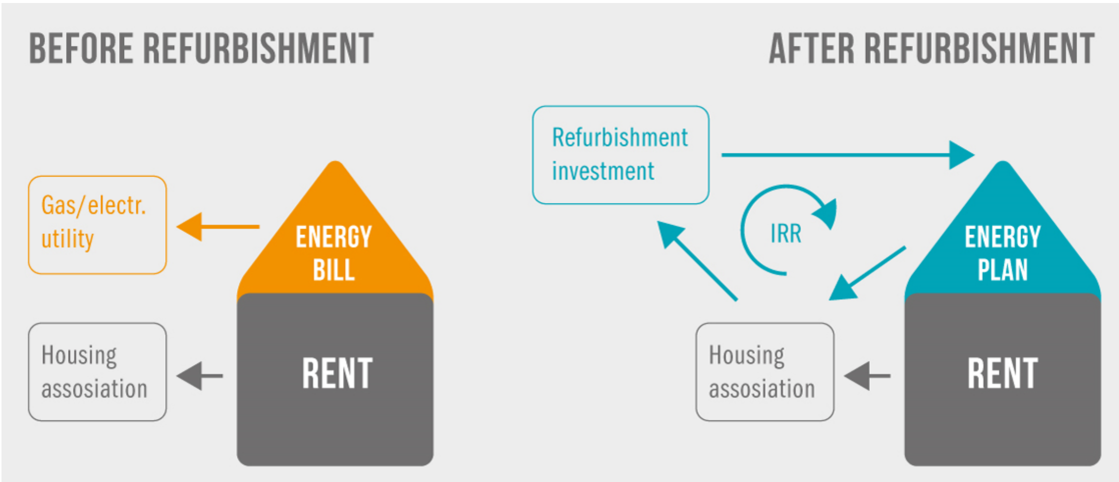


Figure 2.3.3 Energiesprong economic model (UK, 2024).

A central point of the method is the fairly high-performance economic model. The real estate companies invest in the renovation and the tenants, who in traditional conditions would pay rent to companies and bills to energy suppliers, give the money directly to the investors only, so that the redevelopment is financed by funds that are usually spent for energy bills. However, to avoid possible increases in energy prices, the value of the investment is fixed in advance ((ECSO), 2017) (UK, 2024).

1.3.1.1. Benefits

The prefabricated façades, and particularly the Energiesprong retrofit method, offer several benefits for homeowners and the environment as described in great lengths earlier in the thesis:

- **Energy efficiency**
  The use of prefabricated insulated walls translates to significant reductions in energy bills and by employing smart green technologies such as heat pumps and solar panels, the building generates enough renewable energy to meet its heating, hot water, and electrical appliance needs.
- **Improved comfort**
  The insulation panels also decrease the problem of insulation, airtightness, and moisture resistance, addressing drafts and leaks due to a high percentage of off-site work done directly inside a factory. It leads to a more consistent and comfortable indoor temperature year-round.
- **Faster turnaround times**
  A key aspect of Energiesprong is the implementation of prefabricated building components that permit quicker installation times and minimize disruption for occupants since only the installation process takes place onsite; basically, within a week of starting work.
- **Cost/long-term effectiveness**
  The upfront costs of an Energiesprong renovation are balanced by the substantial energy savings that will be experienced over the next 30 years, time guaranteed by the Solution provider responsible for designing and installing the performance of the outcome specified (Palmer, et al., 2022).
- **Environmentally friendly**
  These typologies of retrofits aim to achieve net-zero consumption with roughly 90% energy/CO_2 saving and managing factors such as overheating. Doing so, reliance on conventional energy sources is reduced (Palmer, et al., 2022).

1.3.1.2. Drawbacks

Energiesprong renovation method, prefabricated elements-based, does have some drawbacks that are important to consider:

- **Financing**
  One of the main drawbacks is the initial cost of the retrofit. While in the long-term the method aims to be cost-effective by reducing energy bills and maintenance costs, the upfront investment translated into the capability to get prefabricated insulated wall and roof panels, smart green technologies and other components can be significant, hence a barrier for some homeowners or housing providers.

- **Limited applicability**
  The intervention relies on a standardized approach with prefabricated components which may limit the flexibility of the process. The most suitable cases are single-family homes or similar detached buildings, whereas it can be challenging for larger structures or those with unique architectural features, such as historical façades.
- **Regulatory challenges**
  While regulations play a key role in the success of the Energiesprong setup, there can be challenges in ensuring compliance with existing regulations or in establishing new standards at the EU level. Regulatory hurdles can impact the scalability and adoption of the Energiesprong method in different regions.
- **Aesthetics**
  The prefabricated nature of the components used in retrofits may limit the aesthetic options available for landlords. In terms of design customization, it may not offer so much flexibility and disappointing whoever is seeking a highly personalized renovation.
- **Potential for disruption**
  During the construction phase disruption can arise even though installation is faster than traditional renovations, particularly in the presence of unforeseen complications. Due to modularity, some dismantling of existing building elements may be necessary.
- **Limited track record**
  Since the approach is relatively new, the long-term performance in different climates and with various building types is still being evaluated.
- **Finding qualified contractors**
  For the complexity of the application, the method requires specialized expertise and contractors familiar with it. The availability of qualified professionals in the area may be challenging.

1.3.2. Stratigraphy of a Façade Module Sample

A typical façade module of ventilated façade solution is:

Solution A3	
No.	**Component**
1	Expansive PU foam
2	Stainless steel anchor
3	Screw anchor
4	Mineral wool with Air&Vapour barrier
5	Timber frames
6	Mineral wool
7	Wooden wind barrier
8	Air cavity
9	HPL panel
10	Existing wall

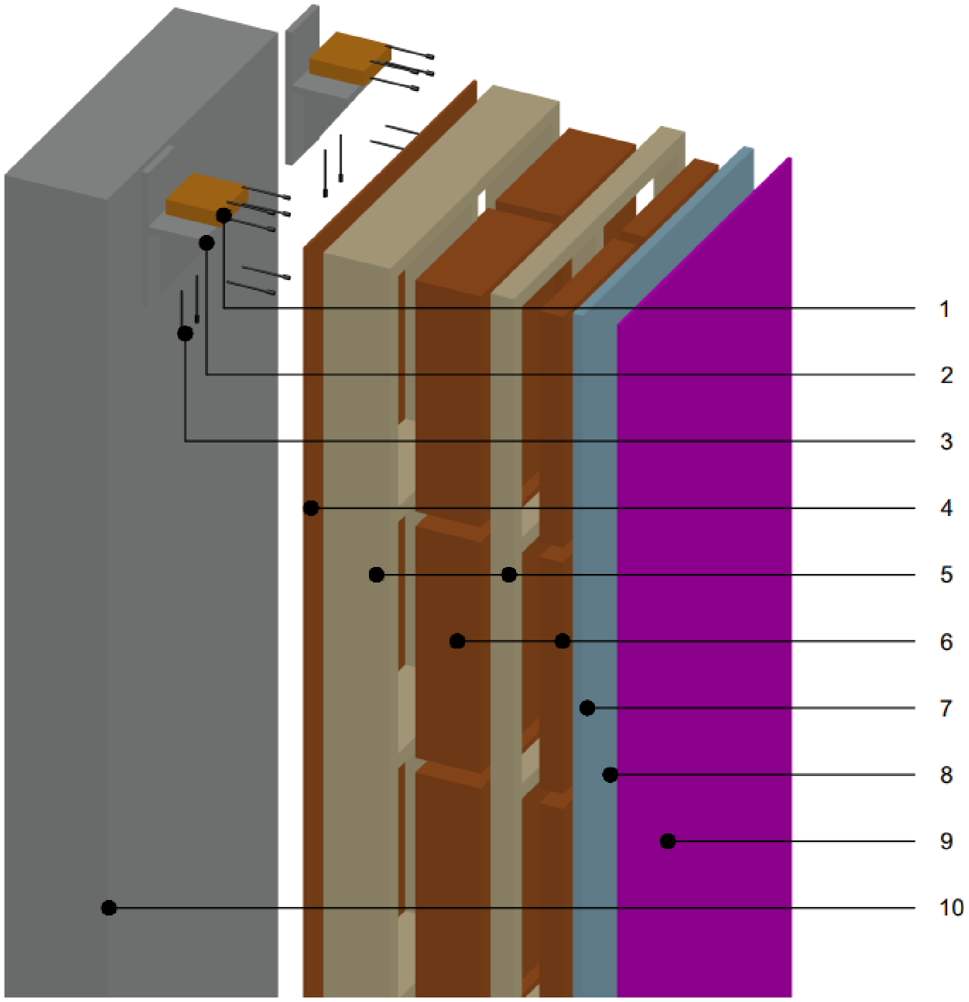


Figure 2.3.4 Prefabricated façade stratigraphy (by the author).

3. MULTI-CRITERIA ANALYSIS (MCA)

Beginning with the research mentioned above's question, the design of the building envelope must be assessed considering the topic of sustainability, which is the capacity to maintain or improve the state and availability of desirable materials or conditions over the long term. It encompasses a balance of three interconnected pillars: environmental sustainability which focuses on protecting and conserving natural resources and ecosystems, economic sustainability which involves creating systems and practices that support long-term economic growth without negatively impacting social, environmental, and cultural aspects, and social sustainability which emphasizes the well-being of individuals and communities.

Evaluating building envelope design frequently requires intricate decision-making processes and must consider the interplay between these three pillars to achieve a sustainable and harmonious outcome. Here is the need to consider multiple criteria simultaneously, taking into account both technical elements, which are based on empirical observations, and non-technical elements, which are based on social visions, preferences, and feelings. In this context, a handy aid is provided by the techniques that are part of the Multiple Criteria Analysis (MCA) family. By employing MCA methodologies, stakeholders in façade renovation projects can make informed decisions that balance diverse criteria and lead to optimal outcomes. This approach not only enhances the efficiency and effectiveness of the decision-making process but also helps achieve a harmonious blend of architectural aesthetics, structural integrity, energy efficiency, and overall performance in building envelope projects.

Multi-criteria analysis appeared for the first time in the 1960s as a decision-making tool. Nonetheless, the analysis grew mainly in the last decades due to the continuous rise in awareness that the solutions to real problems, always more complex, can bring diverse answers (Roscelli, 2014).

MCA is a method used to compare and assess different projects or measures by considering numerous criteria simultaneously in a complex situation. It helps decision-makers integrate various options, reflecting stakeholders' views, to provide guidance or recommendations for future actions; the active involvement of decision-makers is crucial in this process. MCA establishes preferences among options based on an explicit set of objectives and measurable criteria, and the aggregation of data for overall performance evaluation is dealt with as well. Unlike Cost-Benefit analysis, which is a mono-criteria evaluation technique that expresses the judgment as a function of monetary variables only, the Multi-Criteria analysis expresses decisions on a normalized scale and afterward weighted among each other; the term of comparison can be reached by different paths (Government, 2009).

A widely utilized form of MCA that has found many applications in both public and private sector organizations is multi-criteria decision analysis, abbreviated as MCDA (also referred to as multi-attribute decision analysis, or MADA).

"MCA is an umbrella term to describe a collection of formal approaches which seek to take explicit account of multiple criteria in helping individuals or groups explore decisions that matter" - V. Belton and T. J. Steward.

For what concerning MCA methods, a bunch of classifications exist, deriving from different theories and scientific methodologies. They can be quite helpful for practical decision-making, but some may not be as useful. All MCA approaches make the options and their contribution to different criteria clear, and they all require good judgment. However, the methods differ in how they combine the data. The main purpose of these techniques is to address the difficulties that human decision-makers often have in handling large amounts of complex information consistently.

MCA techniques can be used for shortlisting a few options for further detailed evaluation, for identifying a single most preferred option, for ranking the options, or for simply distinguishing acceptable from unacceptable possibilities (Government, 2009).

The first classification contains discrete multi-criteria or continuous multi-objective methods; in particular, for the discrete problems, the subdivision splits into four types of evaluation which contribute as support to the decision maker:

- *Choice.* Picking out the best alternative, or a limited number of best alternatives.
- *Rank.* Listing down the alternatives from the best to the worst ones.
- *Description.* Identification of the main distinguishing features each alternative owns.
- *Classification/Sorting.* Categorization of alternatives into predefined homogeneous groups (Roscelli, 2014).

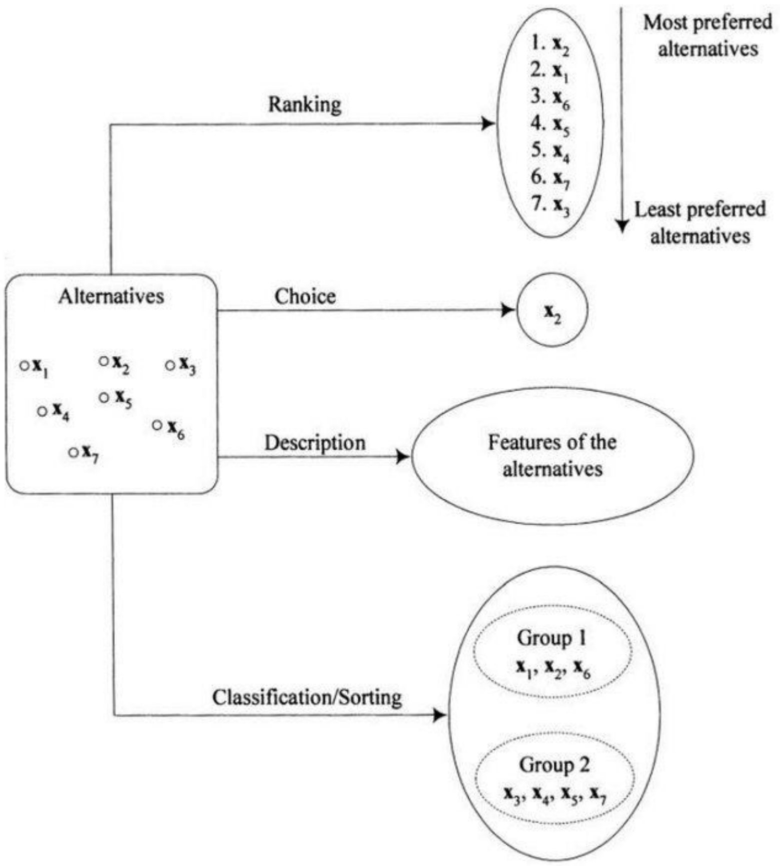


Figure 2.3.1 Decision problem model diagram (Lopez-Irarragorri, Miguel, Llanes, & Garza-Morales).

Another classification of the methods concerns the nature of information to be dealt with, and it is possible to distinguish among:

- Quantitative (or hard) methods that use hard information and quantitative data. Examples are weighted sum and ELECTRE methods.
- Qualitative and mixed (or soft) methods that use soft information mainly and qualitative data. Examples are the frequency analysis method, REGIME ones, EVAMIX method, Analytic Hierarchy Process (AHP), and Analytic Network Process (ANP).

The last classification is made according to the procedure taken by the decision maker for choosing the favorite alternative; the categories are:

- Outranking-based approaches, in which the outranking relation is built through a series of pairwise comparisons of the alternatives. ELECTRE and PROMETHEE methods are part of it.
- Multi-Attribute Utility theory is taken as a reference for this category so that the process becomes easier and is applied whenever indices are aggregated through a weighted summation. For instance, the Analytic Hierarchy Process (AHP) and Analytic Network Process (ANP) appear in this category (Roscelli, 2014).

A full application of MCA normally involves eight stages:

1. Establish the decision context
2. Identify the options
3. Identify the objectives and criteria that reflect the value associated with the consequences of each option
4. Describe the expected performance of each option against the criteria
5. "Weighting". Assign weights for each of the criteria to reflect their relative importance to the decision
6. Combine the weights and scores for each of the options to derive an overall value
7. Examine the results
8. Conduct a sensitivity analysis of the results to changes in scores or weight

STEP 1 – Establish the decision context

To begin with, MCA should establish the aims of the study to avoid leading a wonderful analysis for the wrong problem, which does not mean the purpose stays fixed throughout the analysis, but the evaluation needs to have a clear, well-defined starting point. Articulating the initial objectives is crucial to structuring the subsequent stages of the analysis effectively. Having clear objectives for the MCA assists in delineating tasks for the following stages and maintains focus throughout the study.

Involving key players in MCA is essential. These individuals, known as stakeholders, represent important perspectives and values in the decision-making process. While stakeholders may not physically participate in the MCA, their values should be reflected through selected key players who actively contribute to the analysis. To obtain the best result from the examination conduction, the social and technical aspects of the system must be considered together. This can be done by adopting the approach of facilitated workshops, where participants, including interest groups and key players, come together. Led by an impartial facilitator, the group navigates through the various stages of the process, and with the help of computer programs for multi-criteria analysis for modeling scenarios in real time, the facilitator displays the results for all participants to observe.

Answering some questions, such as: What goals are to be achieved? What is the current situation? What strengths can help achieve the goals and what weaknesses can block achieving that? will assist in providing a setting for the analysis. The MCA might be structured to:

- Show the decision-maker the best way forward
- Identify the areas of greater and lesser opportunity
- Prioritize the options
- Clarify the differences between the options
- Help the key players to understand the situation better
- Indicate the best allocation of resources to achieve goals
- Facilitate the generation of new and better options
- Improve communication between parts of the organization that are isolated
- Any combination of the above

STEP 2 – Identify the alternatives to be appraised

Having established the decision context, the next step is to list the set of options to be considered. When a predetermined option is in place, there is a temptation to treat it as definitive and conclusive. A common error of the human being is to attempt to analyze just one option, considering no other alternative at all; brainstorming to point out the threats that can arise, should be done.

STEP 3 – Identifying criteria and sub-criteria

Another important step is the selection of criteria and sub-criteria as instruments for assessing the consequences of each option, in other words, they are performance measures also considered as "value-added" to the formal MCA process, by which the alternatives will be judged. In support of that, criteria need to be operational and for each criterion, there must be a way to measure or judge how well each option meets the objectives expressed by that criterion.

Differentiating what is a good choice or a bad one in the decision problem is a key point. Incorporating interest group perspectives in multi-criteria analysis can be reached by involving affected parties directly, analyzing policy statements and secondary sources for criteria, or having team members role-play key interest groups to ensure their viewpoints are considered during criterion derivation.

When conducting the examination, the number of criteria should be kept as low as possible while allowing for a well-informed decision. There is no universal rule to determine the optimal number of criteria, as this will vary depending on the specific application and decision context; generally speaking, criteria are specific, measurable objectives. It's common usage to arrange the criteria by grouping them under higher-level and lower-level objectives in a hierarchy, which is often referred to as a value tree.

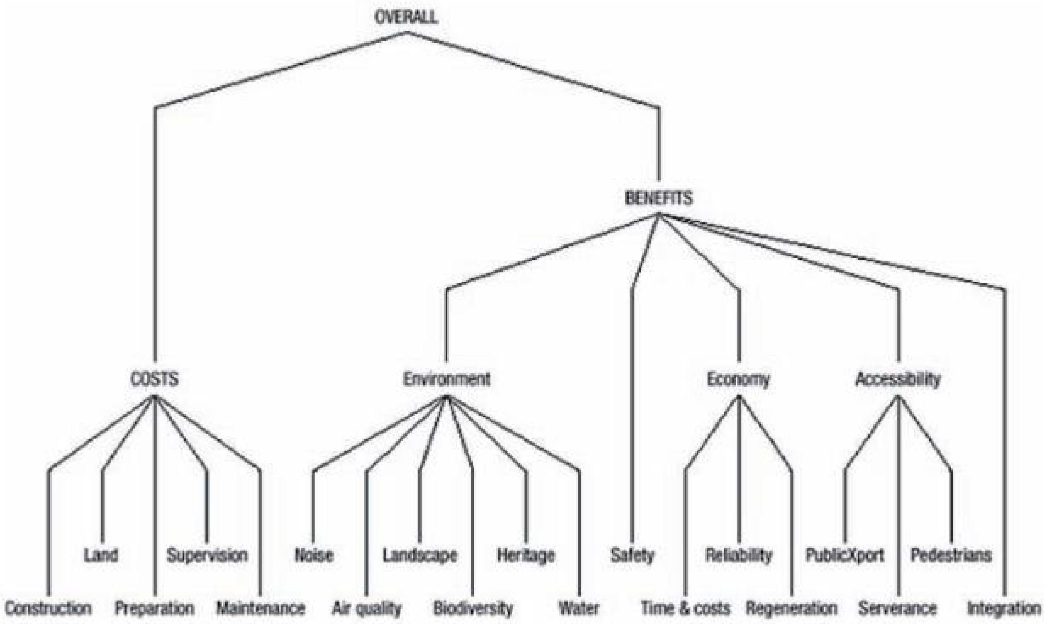


Figure 2.3.2 A value tree for objectives (Government, 2009).

STEP 4 – Describe the expected performance of each option against the criteria

Following the definition of projects and criteria, a quantitative assessment or a qualitative description of the impact of each project, in terms of criteria, must be undertaken.

Talking about complex situations, the necessity of writing down a table of consequences per each option can arise. On the other hand, based on judgment criteria and actions to be assessed, the decision makers create a unique multi-criteria evaluation matrix, also called the performance matrix, involving all the options in it. The matrix is structured as a table with columns corresponding to the number of criteria and rows corresponding to the number of actions being compared. In particular, each row represents an option, and each column assesses the performance of options across different criteria; hence every cell signifies the evaluation of a specific action for a particular criterion.

MCA necessitates an evaluation of all the criteria, but does not demand that all evaluations take the same form. Specifically, individual performances are commonly measured in cardinal numbers, but can also be presented as bullet point scores or color coding.

STEP 5 – Assess weights for each of the criteria to reflect its relative importance to the decision

The concept of weighting is strictly linked to the evaluation method developed in the multi-criteria analysis and can assume several meanings. Overall, numerical weights are assigned to each criterion to define the relative valuations of a shift between the highest and lowest points on the chosen measurement scale.

Preference scales cannot be merged directly since a unit of preference on one scale may not correspond to the same unit of preference on another scale; after choosing the right weighting procedure, the comparison becomes meaningful.

The most used method utilized by the proponents of the MCA is "swing weighting", which can be achieved with a group of key players using a 'nominal group technique. To begin with, the one criterion having the biggest swing in preference on a ranking from 0 to 100 is recognized. If the examination collects a small number of criteria, this can be easily found with agreement from participants, on the contrary case, with numerous criteria, a pairwise comparison process may be needed to identify the criterion with the largest swing in preference. The latter consists of comparing criteria two at a time for their swing in preference and always keeping the one with the largest swing, being afterward, compared with a new criterion.

STEP 6 – Calculate overall weighted scores at each level in the hierarchy

The task of obtaining the final value is typically automated using computers, although a calculator can be sufficient in some cases. The overall preference score for each option is calculated as the weighted average of its scores across all criteria.

Supposing that the preference score for option i on criterion j is represented by s_{ij} and the weight for each criterion is represented by w_j, then with n criteria the overall score for each option S_i is given by:

$$S_i = s_{i1}w_1 + s_{i2}w_2 + \cdots + s_{in}w_n = \sum_{j=1}^{n} s_{ij}w_j$$

STEP 7 – Examine the results

The weighted average of all the preference scores is a way to get the top-level ordering of options and going through the total scores, an indication of how much better one option is over another is given. However, MCA can unveil unexpected outcomes requiring careful consideration before making decisions. In such cases, creating a provisional decision-making system to address unforeseen results and explore the insights brought to light by the multi-criteria analysis might be essential. This system involves a series of collaborative meetings that end up in recommendations presented to the ultimate decision-making authority. During these sessions, participants are tasked with examining the MCA outcomes, validating the findings, assessing potential organizational impacts, and crafting actionable proposals for the future direction.

STEP 8 – Conduct sensitivity analysis

The last phase of the MCA is the sensitivity analysis, which allows examining how uncertainties in the inputs or disagreements between people can impact the final overall results. Experience shows that MCA can help decision-makers reach more satisfactory solutions in these situations:

- Consulting interest groups ensures the MCA model includes criteria that matter to all stakeholders and key players
- Interest groups often differ in their views on the relative importance of criteria and some scores, with weights being more contentious than scores
- Sensitivity analyses can reveal ways to improve options and help resolve disagreements between interest groups

By incorporating this analysis, MCA can navigate the challenges posed by vagueness and differing perspectives, leading to more robust and acceptable decisions (Government, 2009).

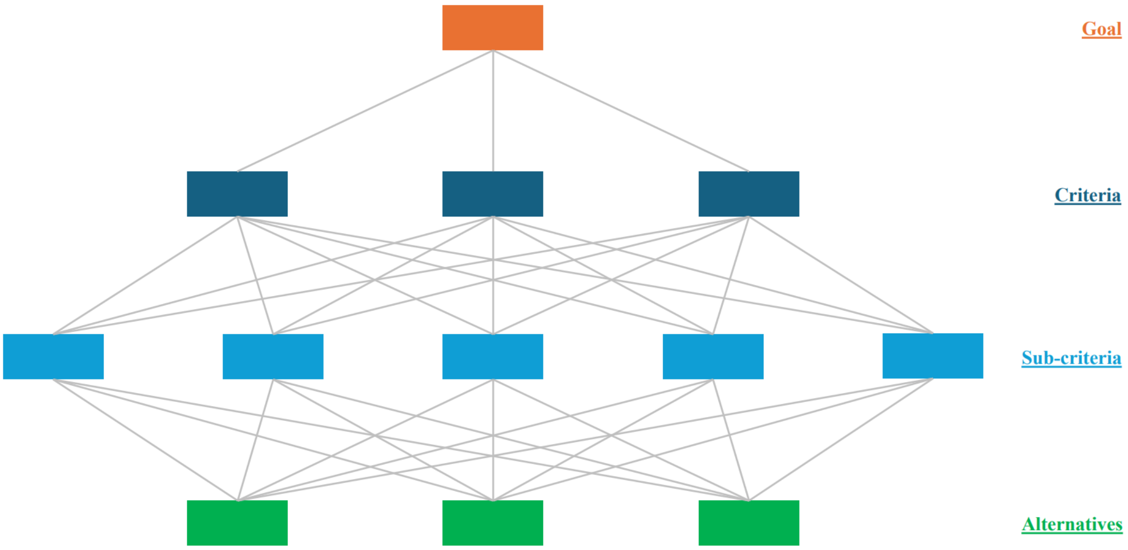
3.1. Analytic Hierarchy Process (AHP)

Among the wide variety of existing multi-criteria models, the current study focuses on the use of the Analytic Hierarchy Process. AHP is one of the most versatile decision-making tools for selecting the optimal alternative. Both measurable and unmeasurable factors can be studied. It has been used in many different areas and for various purposes to assess the priority and feasibility of all kinds of projects. The main idea behind AHP is that when people make choices, their experience and knowledge are just as important as the data they look at. It provides a non-linear framework that can consider a huge number of variables at once, such as the physical and economic environment, social and cultural factors, and so on. This allows it to explicit hierarchical structures founded on the given objectives, and to identify feasible paths between them, with each path weighted according to its importance. It is a tool that has found uses in a wide range of problem sectors from environmental impact assessment, allocation of economic resources, resolution of conflicts, and interventions both at urban and territorial scales to capital-intensive decisions (Saaty & Vargas, 1982).

Professor Thomas L. Saaty designed the method at the University of Pittsburgh in the mid-1970s; it is utilized to evaluate options by comparing them in pairs (pairwise comparison) based on their relative importance or contribution to a defined goal that makes the problem up. It enables the systematic deconstruction of a complex issue into fundamental components, facilitating the comparison of each pair of data elements to establish a priority ranking among alternatives within each level of the breakdown. Within the hierarchical framework of the Analytic Hierarchy Process (AHP), both subjective assessments and objective data can be seamlessly integrated. This model effectively handles information of diverse types, blending qualitative and quantitative aspects by converting experts' subjective judgments into a 9-point scale. Upon completion of the evaluation process, it generates a set of cardinal indices that allow for arithmetic operations such as addition, subtraction, multiplication, and division.

The procedure is based on three fundamental principles:

- **Hierarchical decomposition of the problem**
  The decomposition principle is applied by structuring a complex problem in a hierarchical manner. The elementary parts are grouped into homogeneous sets (clusters) of elements comparable to each other and independent from those in the succeeding levels, working downward from the overall focus at the top level. For hierarchical structure implementation, the context, stakeholders, stakeholders' goals, and criteria need to be clear. Generally, the number of levels is dictated by the complexity of the problem and the level of detail that wants to be reached.



- **Comparative judgment method**
  It consists of comparing in pairs the elements in some given level with respect to each criterion or property in the level above, giving rise to matrices. The matrix values come out by answering questions: "Given a criterion and two alternatives A and B, which alternative satisfies it more and how much more?"; to describe how much a criterion is important over another, a 9-point rating scale made by Saaty is adopted.

Numerical value	Description
1	Equal importance
3	Slight importance of one over another
5	Moderate importance of one over another
7	Very strong importance
9	Extreme importance of one over another
2,4,6,8	Intermediate values between two adjacent values

*"For each level, it is necessary to build as many square matrices -of pairwise comparison between elements- as there are elements ordered above. If **n** is the number of elements to be evaluated at a given level and **m** is the number of elements at a higher level, **m** matrices must be elaborated: **n x n**."* (Roscelli, 2014)

- **Synthesis of priorities**
  The information within the pairwise comparison matrices is utilized to establish the hierarchy of importance among the elements in each matrix. This hierarchy is represented by a set of weights that indicate the ultimate preference of the elements in relation to the reference criterion. Mathematically, the hierarchy is represented as a vector of cardinal values, where each row signifies the priorities among the elements being compared in the pairwise assessments. This vector aligns with the principal eigenvector of the matrix of pairwise comparisons.

$$AX = \lambda_{max} X$$

In which:

$$A = pairwise\ comparison\ matrix$$
$$X = (x_1, x_2, \dots, x_n)^T = eigenvector$$
$$\lambda_{max} = maximum\ eigenvalue$$

Once the largest eigenvalue of the pairwise comparison matrix is found, consistency needs to be checked:

$$CI = \frac{\lambda_{max} - n}{n - 1} = Consistency\ Index$$

$$CR = \frac{CI}{RI} = Consistency\ Ratio$$

Where RI is the Random Index, function of the matrix size. Whether CR is less than 0.1 the results are consistent and valid, otherwise, a revision on the pairwise comparison matrix must be conducted (Roscelli, 2014).

4. CASE STUDIES

In the light of what just explained in the previous chapters, two case studies in Turin have been analyzed with the final purpose of reaching the best solution for the façade renovation among the proposed alternatives. The choice of studying two buildings lies in having structures with different features such as overall dimensions, orientation to the sun, allocation, construction typology, intended use, and public or private construction.

4.1. A Multi-family house in Strada Antica della Venaria

The first case study is a small private building located in Administrative District n.5 (Circoscrizione Amministrativa n.5) composed by Borgo Vittoria, Madonna di Campagna, Lucento, and Vallette districts, within the north-west quadrant of Turin. It's inserted in an urban area characterized by a predominantly residential building fabric with the presence of low buildings of an artisanal nature. In the immediate vicinity is the "Cavallotti" public garden which extends and connects to the other green area located in the central part of the roadway on the northeastern section of "Corso Cincinnato". In the opposite section of that course are the district market and the complex that houses the civic library "Francesco Cognasso" and the headquarters of the local section of the Municipal Police.

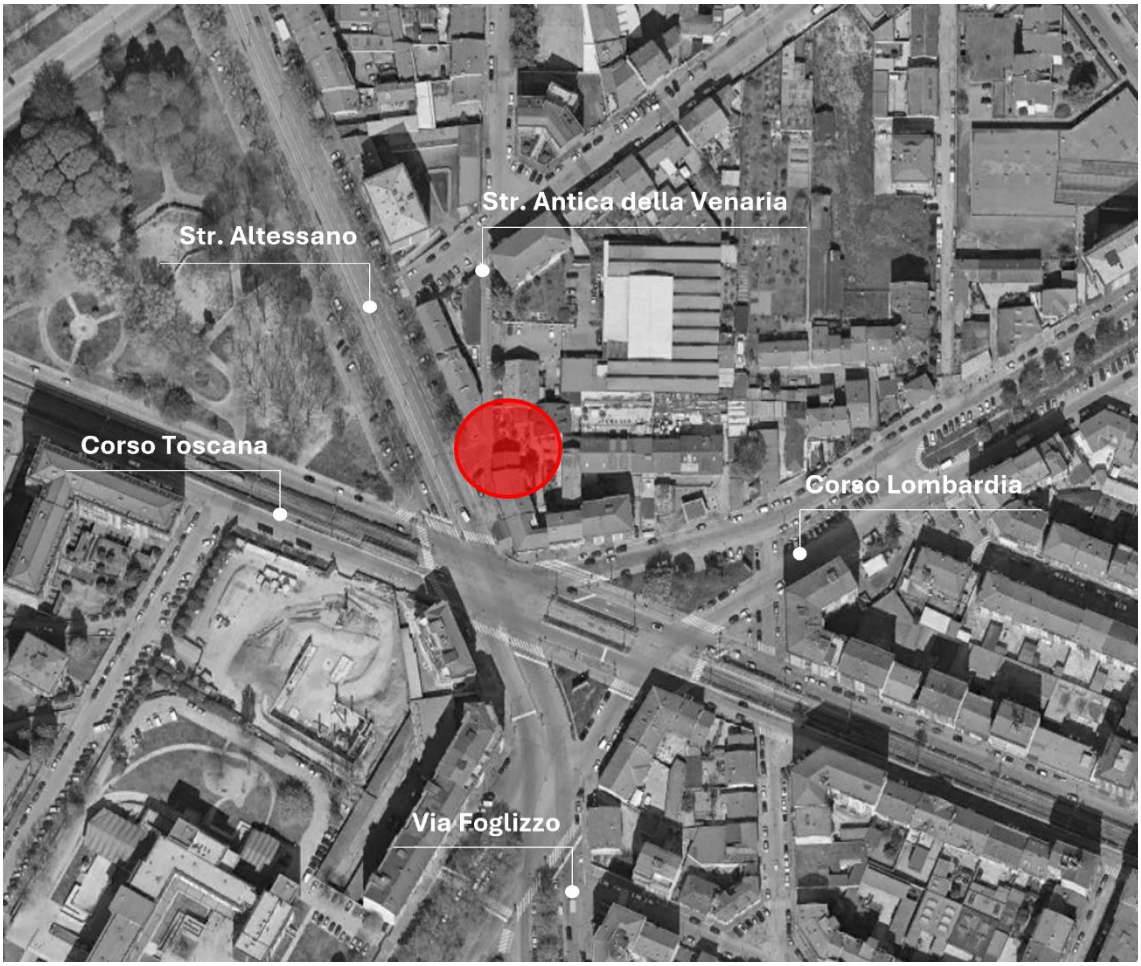


Figure 4.1.1 Multi-family house location in Turin (Google Earth).

The site of interest occupies around 342 MQ in which the multi-family house takes place, and a double indoor parking garage is reached through a common courtyard. The building is tall around 9 meters and it is composed of three stories, one of which is a basement, identified by a masonry self-bearing structure with concrete slabs and the existence of some brick vaults; furthermore, an attic is present and characterized by a double-pitch roof. The main entrance to the complex is in "Str. Antica della Venaria, 4" in which one of the three façades faces the main street (west façade), the other two face the courtyard, and the secondary entrance's road (north and east façades respectively); the fourth side (south one) is adjacent to another building.

Figure 4.1.2 West façade (Google Earth).

Figure 4.1.3 North façade (Google Earth).

Here is a representation of the elevation going under refurbishment through a section:

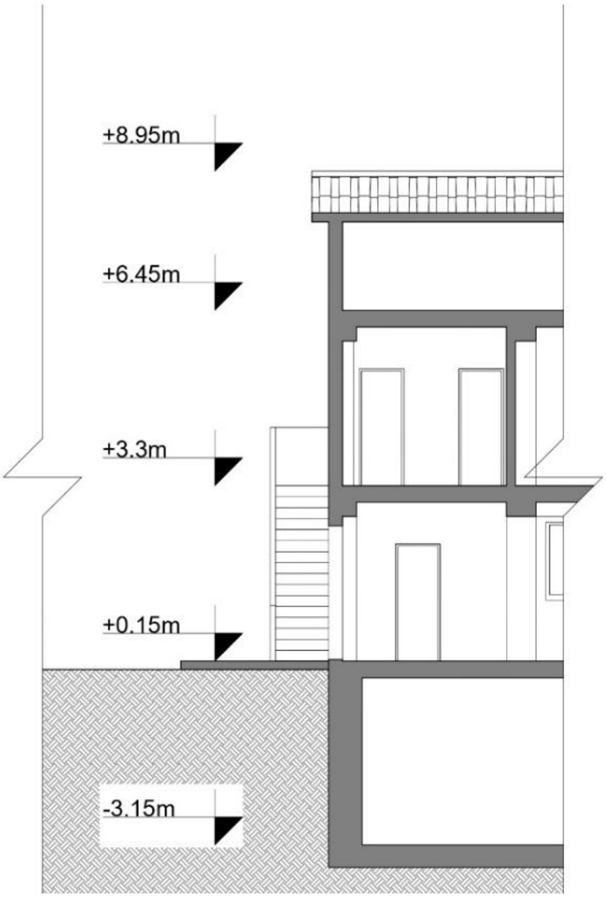


Figure 4.1.4 North sample section of the multi-family house (by the author).

4.2. The building no.8 of ex Manifattura Tabacchi

The second case study is a building with relevant dimensions that is part of the complex of ex Manifattura Tabacchi in Turin. The area is found in the Administrative District n.6 composed of districts such us Barriera di Milano, Regio Parco, Barca, Bertolla, Falchera, Rebaudengo, and Villaretto, within the north-east quadrant of the city. Three main roads - "Corso Parco Regio, Str. alla Manifattura Tabacchi, Via Gabriele Rossetti" - and the Po River touch the ex-factory, well pointing out the hugeness of the whole site. For what concerning the urban fabric, a wide diversity of typologies can be discovered: from the residential one, artisanal one, to the productive fabric. Colletta and Confluenza's parks are giving a spread of green to the surrounding, including a space aimed as a municipal nursery. Unlike the previous case, the entire property of ex Manifattura Tabacchi is state-owned.

After the Treaty of Chateau-Cambresis in 1559, Emanuele Filiberto of Savoia ordered the creation of the Royal Park (Parco Regio). The goal was to incorporate the surrounding agricultural and productive areas into the new capital and organize the area for productive purposes, including the construction of irrigation canals. At the beginning of the 17^{th} century, the construction of the "fishpond" called "Viboccone fountain" was commissioned, as part of a project to create leisure gardens. This fountain would give its name to the Residence, destined to become the official residence of Vittorio Amedeo I.

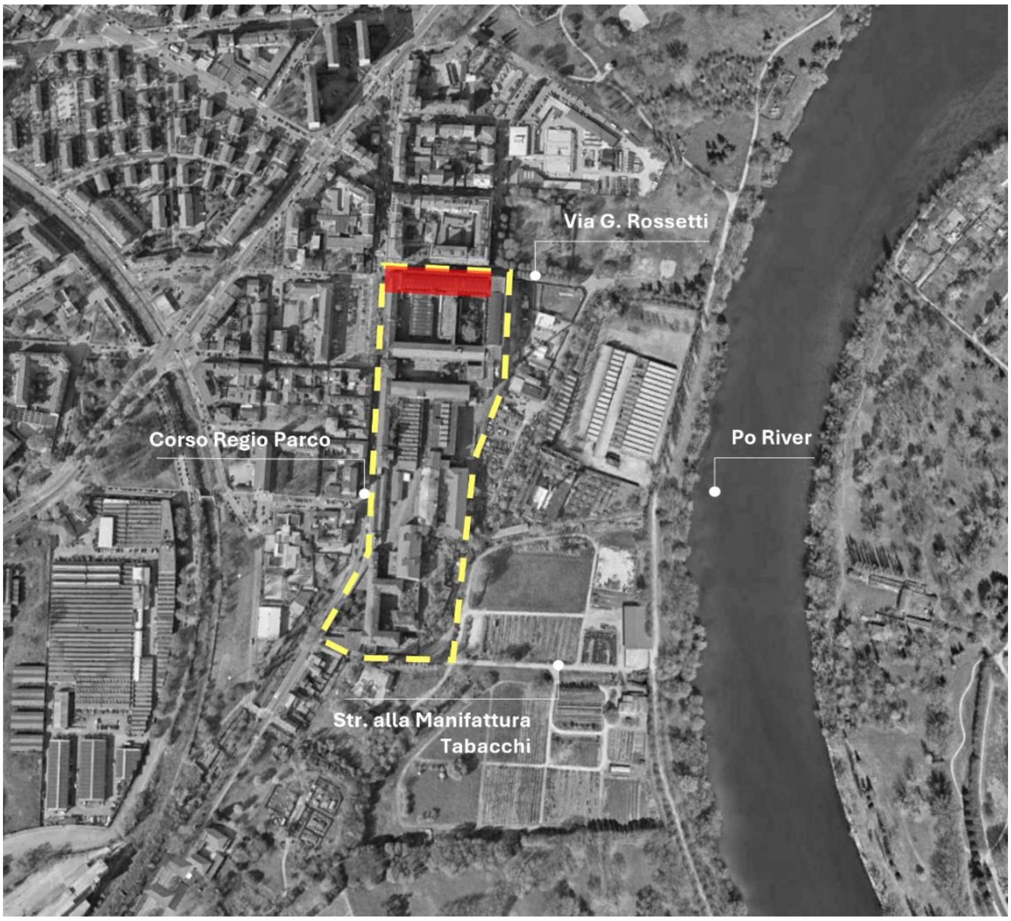


Figure 4.2.1 Ex Manifattura Tabacchi complex location in Turin (Google Earth).

Due to the plague of 1630, the royal family abandoned the palace, marking the beginning of its decline. The castle suffered damage during the French siege of Turin in 1706. During the subsequent urban redevelopment, in 1758 the Regia Manifattura Tabacchi was built on the site of the former palace. The large size of the lot dictated the choice of the site, the proximity to the river, and the elevated position above it, which prevented flooding in the event of high water.

Figure 4.2.2 View beyond Po River, around 1980 (MuseoTorino).

In the first half of the 19th century, with the development of construction techniques, an expansion became necessary with the rise of new buildings. The factory became the largest in the Turin area. At the start of the 20th century, the factory was a true community, with various services within it. In 1918. To speed up the sorting process, it was connected to the Turin-Milan railway. This realization involved the demolition of a factory building and a sharp cut in the façade. During World War II, the factory suffered damage from bombing, forcing the construction of new reinforced concrete structures to replace those damaged or demolished.

In 1952, to make way for a new heating plant, most of the church, the last remnant of Viboccone residence, was demolished. In the 1960s, many types of processing were discounted, leaving the production only for cigarettes. From that moment on, the number of employees began to decline until the factory's closure in 1996.

Figure 4.2.3 Locomotive used for transport, 1984 (MuseoTorino).

The complex occupies an area of about 46.000 MQ constituted from one side by typical wide spaces of the original industrial typology impressive particularly, on the other side by factory bodies. Of the 25 buildings on the site, the one of interest is the number 8. The edifice is included in the third core, which stands for a group of buildings being substituted by new structures. In this particular case, buildings numbers 7-8-9-10 were built after World War II over the previous eighteenth-century buildings' perimeter.

Figure 4.2.4 After the bombing, 8-9th December 1943 (MuseoTorino).

Building number 8 is allocated on the northern part of the complex, presenting one façade only toward the road, the north one, and facing the inner courtyard diametrically, the south façade. With a parallelepiped shape, it stands tall with its three stories and a basement, reaching an impressive height of approximately 22 meters. The roof structure is made by a consistent truss beam allowing the connection of larger spans, making it suitable for various purposes, like during the exercise period. With a total length of around 96 meters, building number 8 shares two sides: the east part is in direct contact with building n.7, and on the opposite side, the west part, shares a common wall with building n.3. On the façade aimed for the renovation, two rows of windows run along the total length of the structure against a background of beige plaster, except for the bottom part colored with a grey tonality - an enclosed balcony figures on the third floor.

Figure 4.2.5 Building no.8's north façade (Google Earth).

Below it is shown a representative section of the façade undergoing renovation, highlighting the building height:

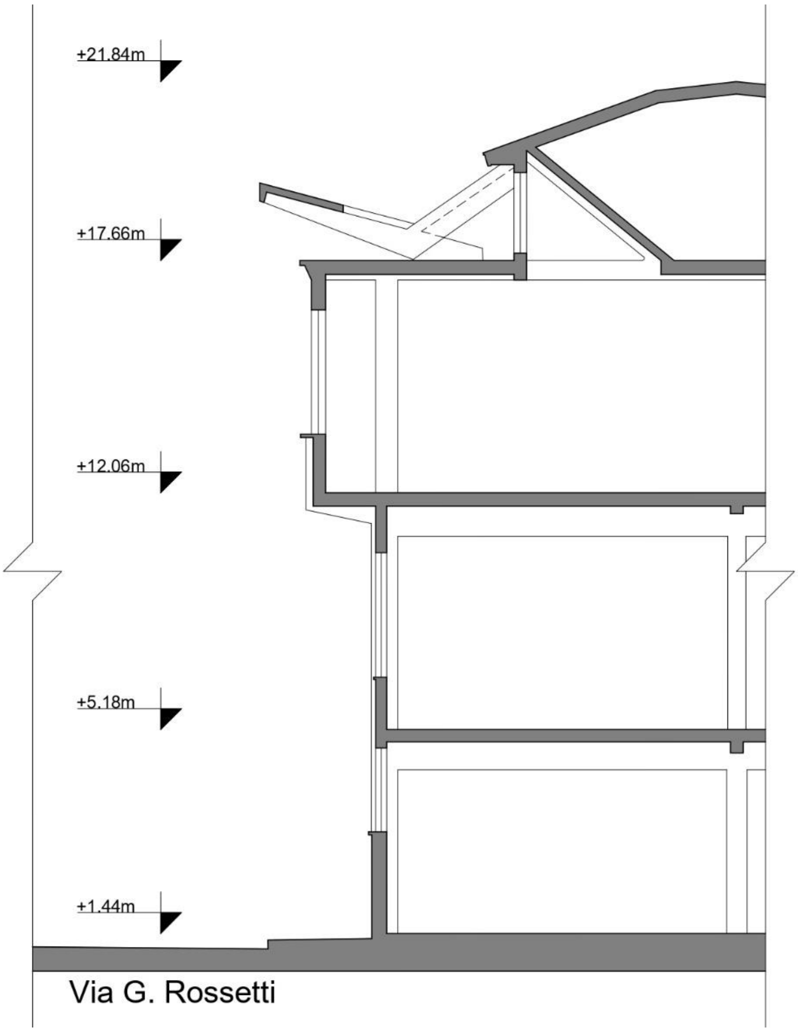


Figure 4.2.6 North sample section of building no.8 (by the author).

5. METHODOLOGY

The approach used in this study to choose the most sustainable façade system for each case study from the various options began with structuring the decision-making process into four hierarchical levels of goal (RQ), criteria (X), sub-criteria/indicators (X.Y), and alternatives (A1, A2, A3), as the requirements of the Analytic Hierarchy Process (AHP) dictate. Subsequently, the main criteria and sub-criteria for the external walls were identified with the help of books, online resources, and relevant reports as information-gathering tools. A questionnaire was then prepared based on the gathered criteria and distributed among a group of professionals. Dealing with crucial fields for the final purpose of designers' choice, engineers were involved in the weight assignment through the pair-wise comparison model of the AHP for every unique criterion using the 1 to 9 Saaty scale. In the final step, the AHP method utilized the identified criteria and their assigned weights to address the decision-making problem.

5.1. Criteria selection

In line with the thesis' objective, the most representative indicators for assessing the sustainability of building envelope renovation were developed. The process began with an extensive literature review, encompassing a wide range of previous studies, books, and scientific articles to identify the main criteria. This comprehensive search led to the selection of three primary pillars of sustainability: Economic (1), Environmental (2), and Social (3). Additionally, a fourth category was introduced to capture various practical, technical, and executive aspects (4). This multi-faceted approach ensured a thorough evaluation of sustainability, integrating both traditional and pragmatic dimensions to provide a holistic assessment framework geared towards integrated design.

To define the sub-criteria, a multidisciplinary database from the publisher Elsevier, known as Scopus, which indexes journals and conference papers, was used. Five significant papers were taken into account as a basis for listing a series of indicators discussed below. The identification of those articles came about through an advanced search which allows you to perform complex search queries by combining multiple search terms that you can link together using Boolean operators (AND, OR, NOT). Two typologies of research were conducted, in order to find as much useful information as necessary, and in particular the used strings were:

- (TITLE-ABS-KEY ("sustainability") AND TITLE-ABS-KEY ("Analytic Hierarchy Process") AND TITLE-ABS-KEY ("facade"))
- (TITLE-ABS-KEY ("sustainability") AND TITLE-ABS-KEY ("AHP") AND TITLE-ABS-KEY ("facade"))

In doing so, evaluating the instrument the thesis wants to provide, nine indicators have been created:

Code	1.1.
Dimension	Economic
Title	Construction cost

Description	The indicator describes the upfront cost of material, labor, and equipment required for the façade renovation module.
Evaluation	The evaluation is based on cost estimates through *Prezzario Regione Piemonte* 2024.
Unit of measurement	Ordinal (0-2)
Values' meaning	Level 0: >€1500 Level 1: ≥€500 and ≤€1500 Level 2: <€500
Sources	(Nadoushani, Akbarnezhad, Jornet, & Xiao, 2017), (Balali & Valipour, 2020), (Gilani, Pons, & Fuente, 2021)

Code	1.2.
Dimension	Economic
Title	Maintainability
Description	It is understood as the ease of inspection of the façade over time, considering the simplicity of performing maintenance tasks.
Evaluation	Understanding whether and how far a design alternative module is inspectable.
Unit of measurement	Ordinal (0-2)
Values' meaning	Level 0: The design alternative is not inspectable Level 1: The design alternative is inspectable (the various layers can be disassembled) Level 2: The design alternative is highly inspectable (the entire module can be disassembled)
Sources	(Gilani, Pons, & Fuente, 2021), (Hassan & Yahya, 2018)

Code	2.1.
Dimension	Environmental
Title	Sustainable resource
Description	The use of recyclable material in the façade renovation.
Evaluation	Counting the average recycling percentage of the stratigraphy layers included in the whole alternative package.
Unit of measurement	Ordinal (0-2)
Values' meaning	Level 0: <25% Level 1: ≥25% and ≤50% Level 2: >50%
Sources	(Nadoushani, Akbarnezhad, Jornet, & Xiao, 2017), (Hassan & Yahya, 2018)

Code	2.2.
Dimension	Environmental
Title	Level Of Recycling (LOR)
Description	It refers to the level of recycled materials and describes the extent to which recycled materials are incorporated into the façade renovation process.

Evaluation	Considering the recycling percentage of the alternatives, do they use recycled materials?
Unit of measurement	Dichotomous (0-1)
Values' meaning	0: No, less than half package is composed of recycled materials; low level. 1: Yes, more than half package is composed of recycled materials; high level.
Sources	(Nadoushani, Akbarnezhad, Jornet, & Xiao, 2017), (Hassan & Yahya, 2018)

Code	3.1.
Dimension	Social
Title	Aesthetic appeal
Description	It is intended as the visual appeal and design quality of a particular façade system that positively influences observers' and users' aesthetic preferences. It involves three parameters: uniqueness (positive innovation in the current trend, style, and shape), medium complexity (façade systems that are neither overly simple nor excessively complex, avoiding chaos), and quality of details (precision and craftsmanship in the installation and assembly).
Evaluation	A 0-3 scale is used to rate these parameters obtained by a questionnaire; the final value is given by the sum of the three answers.
Unit of measurement	Ordinal (0-3)
Values' meaning	Elements influencing observers' judgments on façade aesthetics. Originality, as the level of innovation of the façade alternative in comparison to other façades in the neighborhood (score 0-1): - 0 if <25% - 0.5 if ≥25% and ≤75% - 1 if >75% Medium complexity (score 0-1): - 0 if simple or very complex - 1 if medium level of complexity Details quality, as the percentage of high-quality details in the façade alternative (score 0-1): - 0 if <25% - 0.5 if ≥25% and ≤75% - 1 if >75%
Sources	(Nadoushani, Akbarnezhad, Jornet, & Xiao, 2017), (Balali & Valipour, 2020), (Gilani, Pons, & Fuente, 2021)

Code	3.2.
Dimension	Social
Title	Suitability to location

Description	The harmony and compatibility between the façade alternative module and its neighborhood's style, shape, identity, and ambiance.
Evaluation	It is conducted considering whether the solution fits the neighborhood context.
Unit of measurement	Dichotomous (0-1)
Values' meaning	0: the alternative does not fit into the context 1: the alternative fits into the context
Sources	(Nadoushani, Akbarnezhad, Jornet, & Xiao, 2017), (Balali & Valipour, 2020), (Gilani, Pons, & Fuente, 2021)

Code	4.1.
Dimension	Technical and executive
Title	Structural impact
Description	The potential impact of the façade renovation on the building's structural integrity, including load-bearing capacity, stability, and foundation requirements.
Evaluation	The extent to which the solution impacts the structural integrity of the existing façade.
Unit of measurement	Ordinal (0-2)
Values' meaning	Level 0: the alternative highly affects the integrity; the processing requires strong mechanical fastening or eventually an external substructure. Level 1: the alternative affects the integrity; the processing does require mechanical fastening. Level 2: the alternative does not affect the integrity; the processing does not require mechanical fastening.

Code	4.2.
Dimension	Technical and executive
Title	Time needed for realization
Description	The duration required to complete the refurbishment on-site, including planning, construction, and testing phases.
Evaluation	Days that the realization takes
Unit of measurement	Ordinal (0-2)
Values' meaning	Level 0: > 10 days Level 1: ≥ 5 and ≤ 10 days Level 2: < 5 days

Code	4.3.
Dimension	Technical and executive
Title	Labor requirement
Description	It assesses the need for on-site labor for assembling façade systems.
Evaluation	Number of needed people to build the façade module
Unit of measurement	Ordinal (0-2)

Values' meaning	Level 0: > 4 people Level 1: > 2 and ≤ 4 people Level 2: ≤ 2 people
Sources	(Gilani, Pons, & Fuente, 2021), (Hassan & Yahya, 2018)

Moreover, a translation of the values' meaning is needed to obtain a score that can be later utilized for calculations. For the criteria having the dichotomous scale the translation is not necessary, while for what regards the other criteria being part of the ordinal scale unit of measurement, the levels can be transformed as follows:

- Level 0 corresponds to score 0
- Level 1 corresponds to score 1
- Level 2 corresponds to score 2

It's worth mentioning that the way the sub-criteria, being part of the fourth criterion, have been found relies on the knowledge and the literature studying; employing these tools, three indicators were obtained.

5.2. Quantification of the indicators

The proposed strategies are applied for measuring the sub-criteria related to each façade module solution. The results from their quantification are presented:

Table 5.2.1 Criteria quantification (by the author).

Alternative	Component	Recycling percentage (per kg)	Sustaianable resource (%)	Level Of Recycling (LOR)
A1	Adhesive	0%	30,4	2 out of 6 components are recycled materials
	Mineral wool	75-95%		
	Screw anchor	90-100%		
	Mortar with fiberglass reinforcement mesh	0-5%		
	Fixing agent	0%		
	Silicone finishing	0%		
A2	Neoprene layer	0-10%	79,6	6 out of 7 components are recycled materials
	Aluminum bracket	90-100%		
	Bracket fastener	90-100%		
	Screw anchor	90-100%		
	Mineral wool	75-95%		
	Structural mullion	90-100%		
	PV panel	85-90%		
A3	Expansive PU foam	0-10%	55,0	5 out of 8 components are recycled materials
	Stainless steel anchor	90-100%		
	Screw anchor	90-100%		
	Mineral wool	75-95%		
	Air & Vapour barrier	0-10%		
	Timber frame	50-100%		
	Wooden wind barrier	50-100%		
	HPL panel	0-10%		

According to *Prezzario Regione Piemonte 2024,* the Bill of Quantity (BoQ) of the various options (Table 5.3; Table 5.5; Table 5.7) was conducted, and in the specific case of alternative 3 (A3) a further price analysis was produced, assuming what a typical company would face for estimating the price of prefabricated module mentioned above.

Table 5.2.2 BoQ of alternative 1 (A1) (by the author).

n°	CODE	DESCRIPTION	U.M.	P.U.(€/u.m.)	QTY	TOTAL PRICE [€]
		ALTERNATIVE A1				
1	**01.P25.A60**	*Nolo di ponteggio tubolare esterno eseguito con tubo - giunto, compreso trasporto, montaggio, smontaggio, nonchè ogni dispositivo necessario per la conformita' alle norme di sicurezza vigenti, comprensivo della documentazione per l'uso (Pi.M.U.S.) e della progettazione della struttura prevista dalle norme, escluso i piani di lavoro e sottopiani da compensare a parte (la misurazione viene effettuata in proiezione verticale).*				
	01.P25.A60.005	*Per i primi 30 giorni*	m²	19,22	6,00	115,32 €
2	**01.P25.A91**	*Nolo di piano di lavoro, per ponteggi di cui alle voci 01.P25.A60 e 01.P25.A75, eseguito con tavolati dello spessore di 5 cm e/o elementi metallici, comprensivo di eventuale sottopiano, mancorrenti, fermapiedi, botole e scale di collegamento, piani di sbarco, piccole orditure di sostegno per avvicinamento alle opere e di ogni altro dispositivo necessario per la conformità alle norme di sicurezza vigenti, compreso trasporto, montaggio, smontaggio, pulizia e manutenzione; (la misura viene effettuata in proiezione orizzontale per ogni piano).*				
	01.P25.A91.005	*Per ogni mese*	m²	3,04	12,00	36,48 €
3	**03.A07.A01**	*Realizzazione di isolamento termico a cappotto con lastre di qualsiasi dimensione e spessore, compreso il carico, lo scarico, il trasporto e deposito a qualsiasi piano del fabbricato. Sono compresi inoltre gli oneri relativi a: incollaggio e/o tassellatura e sagomatura dei pannelli, rasatura, stesura di fissativo, applicazione del rasante a base di calce idraulica naturale steso con spatola d'acciaio, compreso fornitura e posa di rete d'armatura e di ogni altro onere necessario per dare l'opera finita a perfetta regola d'arte. (esclusa la sola fornitura dell'isolante)*				
	03.A07.A01.005	*Su superfici interne ed esterne verticali*	m²	51,72	3,00	155,16 €
4	**01.P09.B04**	*Pannelli semirigidi in lana di vetro, Euroclasse A1, di densita' di 40 kg/m³ e lambda pari a 0,032 W/mK per isolamenti termoacustici*				
	01.P09.B04.025	*spessore mm 120*	m²	22,29	3,00	66,87 €
5	**01.P21.B60**	*Vernice siliconica (idrorepellente)*				
	01.P21.B60.005	*In emulsione acquosa (pronta all'uso)*	kg	2,53	2,00	5,06 €
		CONSTRUCTION COST				**378,89 €**

Table 5.2.3 Reference stratigraphy A1 (by the author).

Alternative	Component	Thickness
A1	Adhesive	10mm
	Mineral wool	120mm
	Screw anchor	-
	Mortar with fiberglass reinforcement mesh	10mm
	Fixing agent	10mm
	Silicone finishing	10mm

Table 5.2.4 BoQ of alternative 2 (A2) (by the author).

ALTERNATIVE A2						
1	**01.P25.A60**	*Nolo di ponteggio tubolare esterno eseguito con tubo - giunto, compreso trasporto, montaggio, smontaggio, nonchè ogni dispositivo necessario per la conformita' alle norme di sicurezza vigenti, comprensivo della documentazione per l'uso (Pi.M.U.S.) e della progettazione della struttura prevista dalle norme, escluso i piani di lavoro e sottopiani da compensare a parte (la misurazione viene effettuata in proiezione verticale).*				
	01.P25.A60.005	*Per i primi 30 giorni*	m²	19,22	6,00	115,32 €
2	**01.P25.A91**	*Nolo di piano di lavoro, per ponteggi di cui alle voci 01.P25.A60 e 01.P25.A75, eseguito con tavolati dello spessore di 5 cm e/o elementi metallici, comprensivo di eventuale sottopiano, mancorrenti, fermapiedi, botole e scale di collegamento, piani di sbarco, piccole orditure di sostegno per avvicinamento alle opere e di ogni altro dispositivo necessario per la conformità alle norme di sicurezza vigenti, compreso trasporto, montaggio, smontaggio, pulizia e manutenzione; (la misura viene effettuata in proiezione orizzontale per ogni piano).*				
	01.P25.A91.005	*Per ogni mese*	m²	3,04	12,00	36,48 €
3	**01.A24.F10**	*Fornitura e posa in opera di appoggi a piu' strati con interposti lamierini metallici chimicamente trattati e costituenti un blocco unico, compreso ogni onere*				
	01.A24.F10.005	*In neoprene*	dm³	22,49	0,10	2,16 €
4	**01.P12.E10**	*Profilati laminati di qualunque tipo con altezza superiore a mm 80*				
	01.P12.E10.010	*In lega leggera cromo-alluminio*	kg	6,15	19,00	116,85 €
5	**01.A18.A70**	*Posa in opera di piccoli profilati*				
	01.A18.A70.005	*In ferro, in leghe leggere al cromo, alluminio o in ottone*	kg	4,50	19,00	85,50 €
6	**01.P14.M25**	*Tasselli a percussore in acciaio pieno, corpo cilindrico ed estremità conica, con rondelle di diametro maggiore di 40 mm*				
	01.P14.M25.005	*estremità conica da 8 mm di diametro l=135 mm*	cad	2,30	26,00	59,80 €
7	**01.A08.A40**	*Posa in opera di tasselli ad espansione, di piombo, plastica, gomma o acciaio esclusa la provvista del tassello*				
	01.A08.A40.010	*Su muratura in mattoni pieni*	cad	3,45	26,00	89,70 €
8	**01.P09.B70**	*Lana di vetro per isolamento termo-acustico di pareti in pannelli semirigidi della densita' di 30 kg/m³ e lambda inferiore a 0,035 W/mK; con adeguata protezione di barriera al vapore in vetro nero. Per l'isolamento di facciate ventilate*				
	01.P09.B70.030	*spessore mm 100*	m²	14,67	3,00	44,01 €
9	**03.P14.A01**	*Moduli fotovoltaici a struttura rigida realizzati con celle di silicio mono e poli cristallino, tensione massima di sistema 1000 V, scatola di connessione IP 65 completa di diodi di by-pass, involucro in classe II di isolamento certificato TUV con struttuta sandwich: EVA, tedlar, cella, vetro temperato a basso contenuto di ferro, cornice in alluminio anodizzato, certificazione IEC 61215.*				
	03.P14.A01.050	*Potenza di picco da 105 Wp a 280 Wp*	Wp	0,75	460,00	345,00 €
10	**01.A09.G50**	*Posa in opera di materiali per isolamento termico (lana di vetro o di roccia, polistirolo, poliuretano, materiali similari) sia in rotoli che in lastre di qualsiasi dimensione e spessore, compreso il carico, lo scarico, il trasporto e deposito a qualsiasi piano del fabbricato*				
	01.A09.G50.010	*Per superfici verticali o simili*	m²	11,18	3,00	33,54 €
11	**03.A13.A01**	*Posa in opera di moduli fotovoltaici a struttura rigida in silicio cristallino o amorfo, su struttura di sostegno modulare costituita da profilati in alluminio o acciaio, incluso cablaggio, escluso il nolo di cestello o altra attrezzatura per il trasporto su copertura*				
	03.A13.A01.005	*Su coperture piane o su terreno, superficie installata fino a 100 m²*	m²	87,99	3,00	263,97 €
		CONSTRUCTION COST				**1.192,33 €**

Table 5.2.5 Reference stratigraphy A2 (by the author).

Alternative	Component	Thickness
A2	Neoprene layer	10mm
	Aluminum bracket	80x160mm
	Bracket fastener	-
	Screw anchor	-
	Mineral wool	100mm
	Structural mullion	120x90mm
	PV panel	10mm

Table 5.2.6 Partial BoQ of alternative 3 (A3) (by the author).

ALTERNATIVE A3						
1	**01.P25.A60**	*Nolo di ponteggio tubolare esterno eseguito con tubo - giunto, compreso trasporto, montaggio, smontaggio, nonchè ogni dispositivo necessario per la conformita' alle norme di sicurezza vigenti, comprensivo della documentazione per l'uso (Pi.M.U.S.) e della progettazione della struttura prevista dalle norme, escluso i piani di lavoro e sottopiani da compensare a parte (la misurazione viene effettuata in proiezione verticale).*				
	01.P25.A60.005	*Per i primi 30 giorni*	m²	19,22	6,00	115,32 €
2	**01.P25.A91**	*Nolo di piano di lavoro, per ponteggi di cui alle voci 01.P25.A60 e 01.P25.A75, eseguito con tavolati dello spessore di 5 cm e/o elementi metallici, comprensivo di eventuale sottopiano, mancorrenti, fermapiedi, botole e scale di collegamento, piani di sbarco, piccole orditure di sostegno per avvicinamento alle opere e di ogni altro dispositivo necessario per la conformità alle norme di sicurezza vigenti, compreso trasporto, montaggio, smontaggio, pulizia e manutenzione; (la misura viene effettuata in proiezione orizzontale per ogni piano).*				
	01.P25.A91.005	*Per ogni mese*	m²	3,04	12,00	36,48 €
3	**01.P24.L10**	*Nolo di autogru idraulica telescopica compreso ogni onere per la manovra ed il funzionamento*				
	01.P24.L10.005	*Della portata fino a q 100*	h	56,77	5,00	283,85 €
4	**01.P09.G50**	*Supporto in schiuma poliuretanica dura per appoggio di arcarecci di tettoie, veneziane antisole, marquise e supporto di mensole. per sistemi di isolamento in EPS, lana di roccia e sughero. Come supporto di elevato carichi di compressione, euroclasse B2 di resistenza al fuoco, marchiatura CE, lambda pari a 0,045 W/mK.*				
	01.P09.G50.010	*spessore mm 100*	cad	60,21	2,00	120,42 €
5	**01.A09.G50**	*Posa in opera di materiali per isolamento termico (lana di vetro o di roccia, polistirolo, poliuretano, materiali similari) sia in rotoli che in lastre di qualsiasi dimensione e spessore, compreso il carico, lo scarico, il trasporto e deposito a qualsiasi piano del fabbricato*				
	01.A09.G50.010	*Per superfici verticali o simili*	m²	11,18	0,00	0,01 €
6	**01.P12.E10**	*Profilati laminati di qualunque tipo con altezza superiore a mm 80*				
	01.P12.E10.010	*In lega leggera cromo-alluminio*	kg	6,15	14,00	86,10 €
7	**01.A18.A70**	*Posa in opera di piccoli profilati*				
	01.A18.A70.005	*In ferro, in leghe leggere al cromo, alluminio o in ottone*	kg	4,50	14,00	63,00 €
PARTIAL COST						**705,18 €**

Table 5.2.7 Reference stratigraphy A3 (by the author).

Alternative	Component	Thickness
A3	Expansive PU foam	100mm
	Stainless steel anchor	-
	Screw anchor	-
	Mineral wool	40mm
	Air & Vapour barrier	-
	Timber frame	260mm
	Wooden wind barrier	20mm
	HPL panel	10mm

Table 5.2.8 Price analysis (by the author).

CODE	AP.A3					
DESCRIPTION	Realisation of a prefabricated wooden façade module.					
code	description	U.M.	P. U. [€]	time [h]	quantity	net price
	materials					
01.P09.B60	*Lana di vetro per isolamenti termoacustici di pareti in pannelli flessibili della densità di 18-20 kg/m³; con adeguata protezione di barriera al vapore*					
01.P09.B60.005	*spessore mm 40*	m²	3,69		3,000	11,07 €
01.P15.E40	*Listelli di diverse essenze fino ad una lunghezza di 5 metri*					
01.P15.E40.015	*in castagno (Castanea sativa)*	m³	893,85		0,160	143,02 €
01.P09.B04	*Pannelli semirigidi in lana di vetro, Euroclasse A1, di densita' di 40 kg/m³ e lambda pari a 0,032 W/mK per isolamenti termoacustici*					
01.P09.B04.010	*spessore mm 60*	m²	11,48		3,000	34,44 €
01.P09.B04	*Pannelli semirigidi in lana di vetro, Euroclasse A1, di densita' di 40 kg/m³ e lambda pari a 0,032 W/mK per isolamenti termoacustici*					
01.P09.B04.020	*spessore mm 100*	m²	18,58		6,000	111,48 €
03.P09.I11	*Pannelli in fibra di legno infeltrite e stabilizzate. Densità 200 Kg/m³ . Per cappotti esterni, intonacabile. Lambda <= W/mK*					
03.P09.I11.005	*Spessore 20 mm*	m²	9,43		3,000	28,29 €
30.P25.A15	*Pannelli di compensato/ multistrato longitudinale di pioppo (Populus spp.) e finitura con rivestimento in laminato decorativo ad alta pressione (HPL). Dotati di certificazione di gestione forestale sostenibile o certificazione ambientale di prodotto relativamente al contenuto di riciclato come richiesto dal decreto MITE 23 giugno 2022 paragrafo 2.5.*					
30.P25.A15.005	*Spessore mm 10*	m²	21,36		3,000	64,08 €
	equipment					
01.P26.A20	*Trasporto di materiali di qualsiasi natura dai luoghi di magazzinaggio ai cantieri di costruzione o viceversa con qualunque mezzo, compreso il carico e lo scarico*					
01.P26.A20.005	...	q	2,35		1,634	3,84 €
	labour					
01.P01.A20	*Operaio qualificato*					
01.P01.A20.005	*Ore normali*	h	36,39	6,00	2,00	436,68
01.P01.A30	*Operaio comune*					
01.P01.A30.005	*Ore normali*	h	30,71	3,00	2,00	184,26 €
TOTAL ESTIMATED PRICE						**1.017,16 €**
CONSTRUCTION COST						**1.722,33 €**

The final construction cost (Table 5) of the alternative A3 includes the partial cost of Table 4. Note that the values are draft estimates, as they can vary significantly based on the specific refurbishment requirements and constraints.

The normalized indicator scores of the different façade renovation options are:

Table 5.2.9 Normalized scores (by the author).

Alternative	Construction cost	Maintainability	Sustainable resource	Level Of Recycling (LOR)	Aesthetic appeal	Suitability to location	Structural impact	Time needed for realization	Labor requirement
A1	1	0	0,5	0	0,5	1	1	0	1
A2	0,5	0,5	1	1	0,83	0	0,5	0,5	0,5
A3	0	1	1	1	0,67	0	0	1	0

5.3. Weight assignment

The sustainable design process relies on incorporating project indicators, recognizing that each one impacts the project's outcome; it is essential to assess their influences, also considered as weights. However, even though theoretically the decision-maker is unique, in practice it never happens. To better reflect reality, the final indicator weights were determined by averaging the priorities provided by a bunch of experts, converting the qualitative values into quantitative ones with the Saaty scale. The sample for this study was obtained with the assistance of three figures being part of crucial fields in the façade renovation: an energy professor/engineer (user1) graduate, pioneer of various energetic studies at the international level with a teaching and freelance role over thirty-five years' experience, a structural professor/engineer (user2) graduate, with a teaching and freelance role over seven years' experience, and an architect/professor (user3) graduate, with over twenty years' experience. Each one was asked to assess in pairs the nine indicators by using a quantitative scale from 1 to 9, where:

- 1 means the two indicators have equal importance
- 3 means that indicator A is moderately more important than indicator B
- 5 means that indicator A is more important than indicator B
- 7 means that indicator A is much more important than indicator B
- 9 means that indicator A is absolutely more important than indicator B.

With the help of a comparison matrix, the results of the stakeholders' interviews were transferred to the matrix cells.

Table 5.3.1 Example of comparison matrix for weight assignment (by the author).

	Sub-criteria #1	Sub-criteria #2	Sub-criteria #3	…	…	…	…	…	Sub-criteria #n
Sub-criteria #1	1								
Sub-criteria #2		1							
Sub-criteria #3			1						
…				1					
…					1				
…						1			
…							1		
…								1	
Sub-criteria #n									1

6. RESULTS

Once the indicators were defined, the questionnaires given to the experts returned the final weights necessary for continuing the evaluation. During three individual interviews, each professional was asked to compare the defined sub-criteria in pairs, with the goal of "selecting the most sustainable solution for a building façade renovation" for both case analyses. Through the AHP steps, the definitive solutions have been discovered.

6.1. Multi-family house

Users' individual preferences are displayed here:

Table 6.1.1 User 1 evaluation matrix (by the author).

User 1	Construction cost	Maintainability	Sustainable resource	Level Of Recycling (LOR)	Aesthetic appeal	Suitability to location	Structural impact	Time needed for realization	Labor requirement
Construction cost	1,00	7,00	5,00	5,00	5,00	1,00	0,20	7,00	3,00
Maintainability	0,14	1,00	0,20	1,00	1,00	0,20	0,14	3,00	1,00
Sustainable resource	0,20	5,00	1,00	3,00	3,00	1,00	0,14	3,00	3,00
Level Of Recycling (LOR)	0,20	1,00	0,33	1,00	1,00	0,20	0,14	1,00	1,00
Aesthetic appeal	0,20	1,00	0,33	1,00	1,00	0,33	0,14	1,00	0,33
Suitability to location	1,00	5,00	1,00	5,00	3,00	1,00	0,20	5,00	3,00
Structural impact	5,00	7,00	7,00	7,00	7,00	5,00	1,00	9,00	5,00
Time needed for realization	0,14	0,33	0,33	1,00	1,00	0,20	0,11	1,00	0,33
Labor requirement	0,33	1,00	0,33	1,00	3,00	0,33	0,20	3,00	1,00

Table 6.1.2 User 2 evaluation matrix (by the author).

User 2	Construction cost	Maintainability	Sustainable resource	Level Of Recycling (LOR)	Aesthetic appeal	Suitability to location	Structural impact	Time needed for realization	Labor requirement
Construction cost	1,00	1,00	5,00	0,20	5,00	0,14	0,11	0,20	0,33
Maintainability	1,00	1,00	0,33	0,20	0,33	1,00	3,00	0,33	0,20
Sustainable resource	0,20	3,00	1,00	1,00	0,33	0,33	0,20	1,00	0,33
Level Of Recycling (LOR)	5,00	5,00	1,00	1,00	0,33	0,33	0,20	0,20	0,33
Aesthetic appeal	0,20	3,00	3,00	3,00	1,00	0,33	0,33	0,33	0,33
Suitability to location	7,00	1,00	3,00	3,00	3,00	1,00	0,20	0,20	0,20
Structural impact	9,00	0,33	5,00	5,00	3,00	5,00	1,00	5,00	1,00
Time needed for realization	5,00	3,00	1,00	5,00	3,00	5,00	0,20	1,00	0,33
Labor requirement	3,00	5,00	3,00	3,00	3,00	5,00	1,00	3,00	1,00

Table 6.1.3 User 3 evaluation matrix (by the author).

User 3	Construction cost	Maintainability	Sustainable resource	Level Of Recycling (LOR)	Aesthetic appeal	Suitability to location	Structural impact	Time needed for realization	Labor requirement
Construction cost	1,00	0,20	0,20	0,20	0,20	0,33	0,11	0,20	1,00
Maintainability	5,00	1,00	1,00	1,00	0,33	1,00	0,20	1,00	1,00
Sustainable resource	5,00	1,00	1,00	1,00	0,33	1,00	0,20	1,00	1,00
Level Of Recycling (LOR)	5,00	1,00	1,00	1,00	0,33	0,33	0,20	0,33	1,00
Aesthetic appeal	5,00	3,00	3,00	3,00	1,00	1,00	0,20	0,33	1,00
Suitability to location	3,00	1,00	1,00	3,00	1,00	1,00	0,20	1,00	1,00
Structural impact	9,00	5,00	5,00	5,00	5,00	5,00	1,00	5,00	5,00
Time needed for realization	5,00	1,00	1,00	3,00	3,00	1,00	0,20	1,00	1,00
Labor requirement	1,00	1,00	1,00	1,00	1,00	1,00	0,20	1,00	1,00

After that, the principal eigenvector, that corresponds to the priority vector, of each comparison matrix was found with the help of the geometric mean operation, which is an approximate procedure; then it was normalized.

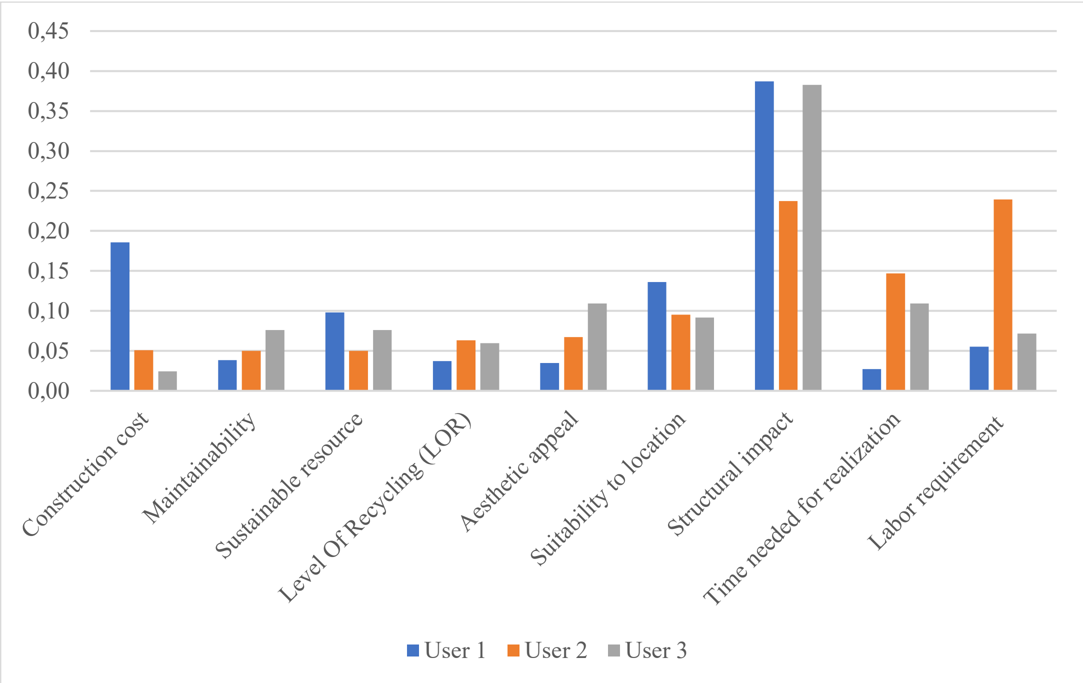


Figure 6.1.1 Priority vectors diagram (by the author).

The final indicator weights are derived as an average of the stakeholders' individual preferences.

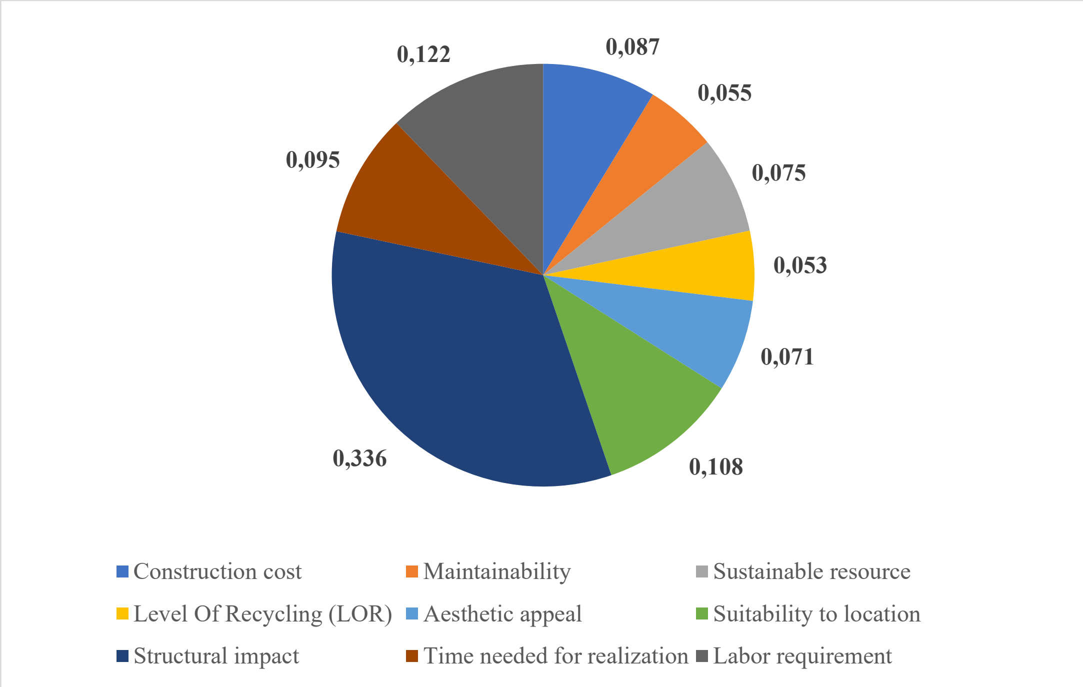


Figure 6.1.2 Final weights (by the author).

The overall scores for each option are given by the weighted averages of their scores (Table 11) across all criteria values (Table 6)

Table 6.1.4 Final result (by the author).

S1	0,725
S2	0,534
S3	0,324

The higher number is represented by the summation 1 (S1) which means that the design alternative 1 (A1) is the answer to the research question (RQ) for this case study.

6.2. Building no.8

Here are displayed the individual user preferences:

Table 6.2.1 User 1 evaluation matrix (by the author).

User 1	Construction cost	Maintainability	Sustainable resource	Level Of Recycling (LOR)	Aesthetic appeal	Suitability to location	Structural impact	Time needed for realization	Labor requirement
Construction cost	1,00	5,00	5,00	5,00	1,00	0,33	0,20	7,00	1,00
Maintainability	0,20	1,00	0,33	1,00	1,00	0,20	0,20	3,00	1,00
Sustainable resource	0,20	3,00	1,00	3,00	1,00	1,00	0,14	3,00	1,00
Level Of Recycling (LOR)	0,20	1,00	0,33	1,00	0,33	0,20	0,14	1,00	1,00
Aesthetic appeal	1,00	1,00	1,00	3,00	1,00	1,00	0,14	5,00	1,00
Suitability to location	3,00	5,00	1,00	5,00	1,00	1,00	0,20	5,00	1,00
Structural impact	5,00	5,00	7,00	7,00	7,00	5,00	1,00	9,00	3,00
Time needed for realization	0,14	0,33	0,33	1,00	0,20	0,20	0,11	1,00	0,20
Labor requirement	1,00	1,00	1,00	1,00	1,00	1,00	0,33	5,00	1,00

Table 6.2.2 User 2 evaluation matrix (by the author).

User 2	Construction cost	Maintainability	Sustainable resource	Level Of Recycling (LOR)	Aesthetic appeal	Suitability to location	Structural impact	Time needed for realization	Labor requirement
Construction cost	1,00	3,00	0,20	0,14	5,00	5,00	3,00	3,00	5,00
Maintainability	0,33	1,00	0,33	0,20	3,00	3,00	3,00	1,00	0,33
Sustainable resource	5,00	3,00	1,00	0,20	5,00	5,00	0,20	3,00	1,00
Level Of Recycling (LOR)	7,00	5,00	5,00	1,00	3,00	3,00	0,33	5,00	3,00
Aesthetic appeal	0,20	0,33	0,20	0,33	1,00	0,33	0,20	0,20	0,33
Suitability to location	0,20	0,33	0,20	0,33	3,00	1,00	0,20	0,33	0,33
Structural impact	0,33	0,33	5,00	3,00	5,00	5,00	1,00	3,00	3,00
Time needed for realization	0,33	1,00	0,33	0,20	5,00	3,00	0,33	1,00	0,33
Labor requirement	0,20	3,00	1,00	0,33	3,00	3,00	0,33	3,00	1,00

Table 6.2.3 User 3 evaluation matrix (by the author).

User 3	Construction cost	Maintainability	Sustainable resource	Level Of Recycling (LOR)	Aesthetic appeal	Suitability to location	Structural impact	Time needed for realization	Labor requirement
Construction cost	1,00	0,14	0,20	0,33	0,20	0,14	0,14	0,20	0,20
Maintainability	7,00	1,00	3,00	3,00	0,33	0,33	0,20	3,00	1,00
Sustainable resource	5,00	0,33	1,00	1,00	0,20	0,20	0,14	0,33	0,33
Level Of Recycling (LOR)	3,00	0,33	1,00	1,00	0,33	0,33	0,20	0,33	0,33
Aesthetic appeal	5,00	3,00	5,00	3,00	1,00	1,00	0,20	5,00	5,00
Suitability to location	7,00	3,00	5,00	3,00	1,00	1,00	0,20	3,00	3,00
Structural impact	7,00	5,00	7,00	5,00	5,00	5,00	1,00	5,00	5,00
Time needed for realization	5,00	0,33	3,00	3,00	0,20	0,33	0,20	1,00	1,00
Labor requirement	5,00	1,00	3,00	3,00	0,20	0,33	0,20	1,00	1,00

Their normalized principal eigenvectors are shown:

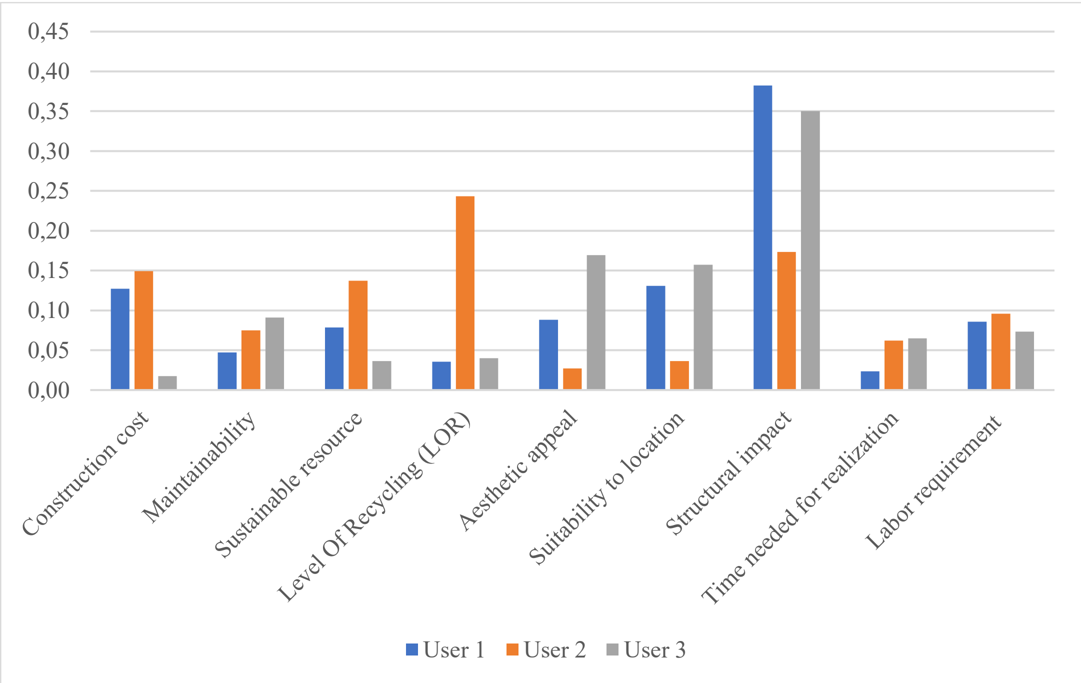


Figure 6.2.1 Priority vectors diagram (by the author).

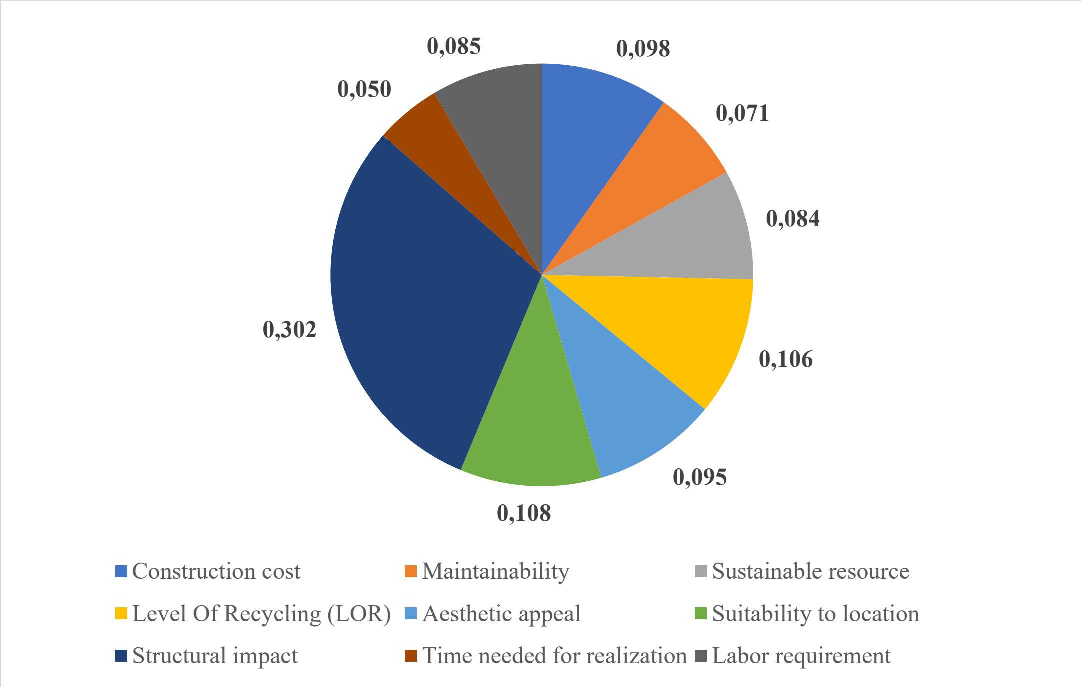


Figure 6.2.2 Final weights (by the author).

Here is the solution to this problem, obtained in the same way as the previous case study.

Table 6.2.4 Final result (by the author).

S1	0,683
S2	0,573
S3	0,375

7. CONCLUSIONS

In this study, a comparison is made between three types of façade systems for the external envelope refurbishment of a couple of existing buildings. The Analytic Hierarchy Process (AHP) conducted the simulation, which integrated representative indicators embarrassing the three dimensions of sustainability, economic, environmental, and social aspects, and technical factors. The involvement of stakeholders throughout the decision-making process ensures that the solutions are comprehensive, inclusive, and tailored to the specific case studies undertaken.

As a result of the surveys derived from evaluation matrices, it is evident that experts (User1 and User3) primarily prioritized the structural impact indicator (4.1), attributing one-third of the total indicator weights to it. Conversely, User2, who has a background in the structural field, paradoxically placed less importance on this factor. In the first case study, User2 gave it equal importance to factors such as labor requirements (4.3). In the second case study, User2 balanced its importance with construction cost (1.1) and sustainable resource use (2.1), while assigning 25% importance to the level of recycling (2.2). In other words, questionnaires demonstrated that aforementioned criteria have been considered as the most important ones.

According to the outcomes, for both application projects, the best choice refers to the alternative with an external thermal insulation composite system (ETICS), with the given code S1. During the performed analysis process, a comparison between two contrary scales of projects with different architectural and technical characteristics was done. Based on it, the expected results could have been various, but the outcome of each project application is the same. The relationship between consequences and indicator rates is highly dependent.

Given the variability of the inputs, like the criteria and questionnaire surveys, the results should not be regarded as absolute. Professionals are advised to tailor the developed methodology to their specific cases. The primary strength of this framework lies in its replicability, which offers significant flexibility for customizing parameters. The main scale is related to the level of detail (LoD) and further in-depth development of a project. A parametric study involving a large number of stakeholders' interests, a group of professionals with related field knowledge, users, and other involved parties, guided by integrated design principles to create harmonious and cohesive solutions that consider all aspects of a project in a holistic and sustainable manner.

In conclusion, this work contributes to the construction industry in embracing sustainability and its goals. It does not only improve communication and resource allocation but also encourages innovation in the field of building renovations. Future research and practical application will conduct a way to move towards sustainable urban development, specifically sustainable façades, to achieve more resilient cities in the future.

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