



HeriTACE

Map of KPI

KPIs assessment framework

Deliverable D5.5

Version N°1.0

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Executive Summary

The ambitions of the European Union (EU) are substantial: to achieve climate neutrality by 2050. The necessity and value of sustainable use and transformation of existing built environment has been emphasized in research for a long time, and one of the most significant challenges in this transition will be the renovation wave of our housing stock, which accounts for 27% of the final energy use of the EU. With this respect, historic cities in Europe present an additional challenge. It is evident that the historically valuable buildings in these cities must be preserved while respecting and considering the inherent heritage and societal values. However, it is unclear how we can balance the aspirations on heritage conservation on individual units with the overarching ambition for climate neutrality at the building stock level.

This report falls under the activities carried out in WP5, Task 5.2 (Definition of concepts and KPIs). Goal of WP5 is the development and validation of a multi-dimensional assessment model (MDAM) for identifying the most appropriate deep energy retrofitting solutions for heritage townhouses within a holistic assessment framework. The goal of the multi-dimensional assessment model is to streamline the evaluation process of energy retrofitting solutions for historical townhouses and the interaction occurring between Building Conservation Authorities and building owners and designers. By defining a set of indicators and their calculation methods, HeriTACE aims at providing the actors involved with a clear, detailed, and objective tool for the evaluation of the performance of deep energy retrofitting solutions.

A screening of indicators developed in past EU projects and proposed by EU and international institutions are used as starting point to define the KPIs framework assessment for HeriTACE. A series of physical and virtual workshops were held among the HeriTACE partners to identify the most relevant KPIs and define the foundation of the assessment framework. In these workshops, the thematic areas according to which the KPIs were going to be grouped were identified as such: Energy and Environmental Impact, Cost, Indoor Environmental Quality, and Heritage and Architecture.

Methods for the calculation of each KPI are provided based on existing ISO and EN standards, or relevant scientific literature. Additional indicators (here named as Performance Indicators, PIs), which are not part of the MDAM, are proposed to give a more comprehensive understanding of the impact of energy renovations solutions on historical buildings. Given the complexity of the framework and the variety of methods and indicators, the proposed indicators and their methods of evaluation will be revised after being tested on some of the case studies in HeriTACE. A new and revised framework will be then produced in Deliverable D5.7 to provide Building Conservation Authorities, building owners, and designers a streamlined and easy-to-use assessment framework.

Abbreviations and acronyms

Acronym	Description
AGA	Annotated Grant Agreement
CA	Consortium Agreement
DoA	Description of the Action - annex 1 to the GA
EC	European Commission
EU	European Union
F&T Portal	Funding and Tenders Portal (EU-portal)
GA	Grant Agreement
HEU	Horizon Europe
PMT	Project management team
PO	Project officer
RP	Reporting period
WP	Work Package
WPL	Work Package Leader
IAQ	Indoor Air Quality
IEQ	Indoor Environmental Quality
LCA	Life Cycle Assessment
MDAM	Multi-Dimensional Assessment Model
KPI	Key Performance Indicator
PI	Performance Indicator
ROI	Return Of Investment
CAPEX	Capital Expenditure
OPEX	Operating Expenditure
NPV	Net Present Value
PDB	Public Domain Benefit
OPP	Overall Payback Period
EPP	Energy Payback Period
PP	Payback Period
GHG	Green House Gas
COP	Coefficient Of Performance
HLO	High Level Objective
PEF	Primary Energy Factor

TPEF	Total Primary Energy Factor
SDG	Sustainable Development Goal
CR	Cost of Reduction
TC	Thermal Comfort

1. Introduction

The ambitions of the European Union (EU) are substantial: to achieve climate neutrality by 2050. The European Green Deal and the New European Bauhaus aim to achieve a sustainable, beautiful and inclusive society through transdisciplinary collaboration and innovation. The necessity and value of sustainable use and transformation of existing built environment has been emphasized in research for a long time, and one of the most significant challenges in this transition will be the renovation wave of our housing stock, which accounts for 27% of the final energy use of the EU. With this respect, historic cities in Europe present an additional challenge. It is evident that the historically valuable buildings in these cities must be preserved while respecting and considering the inherent heritage and societal values. However, it is unclear how we can balance the aspirations on heritage conservation on individual units with the overarching ambition for climate neutrality at the building stock level. More specifically, there is a need for a framework to assess these different aspects at building or neighbourhood level, and offer insights and solutions to address this challenge.

The HeriTACE project investigates how we can future-proof our heritage buildings in a manner that bridges the gap between heritage restrictions and environmental ambitions. The project focuses specifically on small to medium-sized heritage townhouses. Achieving the ambitious goal of climate-neutrality requires a transdisciplinary team to consider all aspects of building performance: heritage value, energy use, environmental impact, indoor climate and user comfort, functionality, cost-effectiveness, and waste management. Heritage restrictions often preclude generic solutions, necessitating innovative approaches to insulation, heating, ventilation, and heat/cold generation.

1.1. Holistic and multi-scale renovation approach for heritage townhouses in historical neighbourhoods

This report falls under the activities carried out in WP5, Task 5.2 (Definition of concepts and KPIs). Goal of WP5 is the development and validation of a multi-dimensional assessment model for identifying the most appropriate deep energy retrofitting solutions for heritage townhouses within a holistic assessment framework. The multi-dimensional assessment model is developed according to the following steps:

1. Develop a comprehensive and interdisciplinary understanding and overview of the heritage townhouse typology, incl. heritage value and its legal framework, building users perspectives) and selection of heritage townhouse archetypes.
2. Obtain insight to and knowledge on experience-based owner/user knowledge and information (case specific) reflecting owner/user needs, requirements, and comfort levels.
3. Develop Holistic set of performance indicators and methods and assemble them in a multidimensional model.
4. Definition of the townhouse baselines and their renovation scenarios.
5. Develop a method to automatically assess the visibility of the (valuable) building parts from the public space Validation of the model on 3 case-studies.

The goal of the multi-dimensional assessment model is to streamline the evaluation process of energy retrofitting solutions for historical townhouses and the interaction occurring between Building Conservation Authorities and building owners and designers. In such an

interaction, different and at times opposing interests, constraints, and perspectives, come into play, leading to a time-consuming process (Figure 1). By defining a set of indicators and their calculation methods, HeriTACE aims at providing the actors involved with a clear, detailed, and objective tool for the evaluation of the performance of deep energy retrofitting solutions.

This report describes the work carried out at point 3 of the above-mentioned list, which consists of the development and definition of energy retrofitting performance indicators (henceforth KPIs assessment framework) and their calculation methods. Qualitative and quantitative KPIs suited for describing the performance of energy retrofitting scenarios of historical buildings have been identified and described in this report. A list of relevant KPIs has been produced to describe the performance of energy retrofitting scenarios for the following parameters: energy use and environmental impact, indoor environmental quality, financial cost, and heritage and architectural value. The definition of the relevant KPIs and their evaluation methods is a key step towards the development of the multi-dimensional assessment model (MDAM) and its application for the performance evaluation of the HeriTACE retrofitting scenarios against the baseline scenarios defined in Task 5.2 and reported in D5.4.

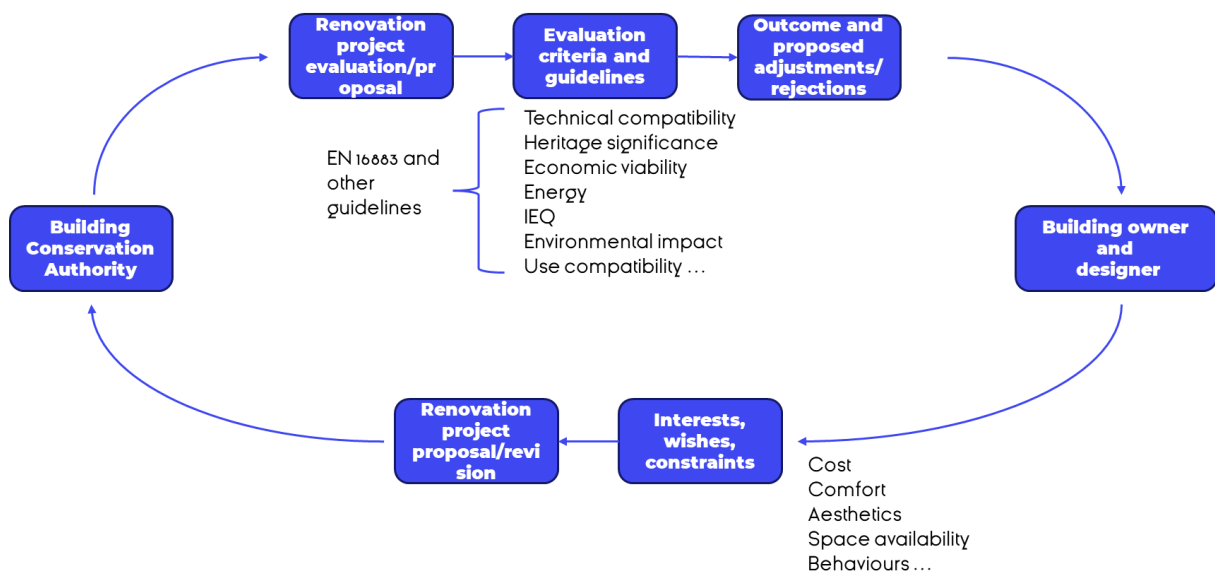


Figure 1. A simplified scheme of process of interaction between building conservation authorities and building owners and designers.

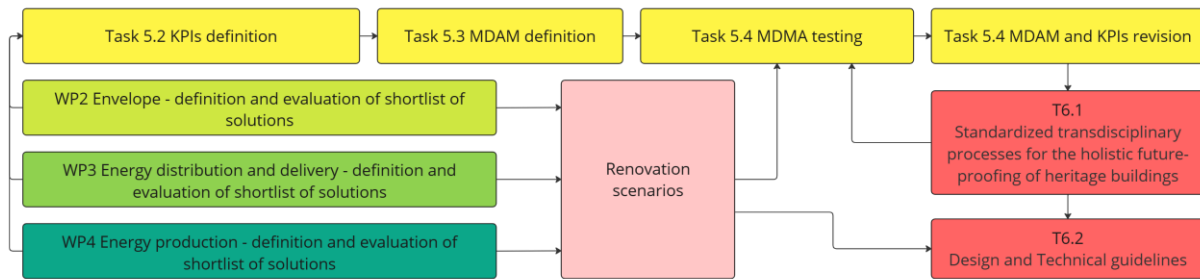


Figure 2. Workflow between KPIs framework definition (Task 5.2), renovation scenarios development (WPs 2-4), MDAM development (Task 5.4), and standardization processes and guidelines (Tasks 6.1 and 6.2)

The development of the KPI assessment framework in Task 5.2 is part of the HeriTACE workflow that brings the evaluation of the shortlist of solutions being developed in the WPs 2 to 4 in the MDAM. As shown in Figure 2, the parallel development and evaluation of the shortlists of solutions in WPs 2-4 gives inputs to the KPIs definition and concurrently defines the HeriTACE renovation scenarios. These are then evaluated in the testing of the MDAM, and the resulting outputs are used for refining the model itself and the KPI assessment framework. The list of relevant KPIs presented in this report is therefore meant to go further editing once the assessment framework will be tested on the renovation scenarios.

2. Method

2.1. Collection of background sources

Indicators for the evaluation of energy retrofitting solutions have been largely investigated in the field of sustainable and retrofitting of buildings towards low/zero energy targets. Such renovation strategies consider the integration of both passive (improvement of the building envelope) and active (installation of on-site renewable energy systems) measures to keep the functionality of existing buildings while reducing their lifecycle energy and costs, and improving the overall indoor comfort of the occupants. These fields do not necessarily deal with historic buildings, but they contribute to the broader goal of transitioning existing buildings towards a carbon-neutral future. This transition is particularly challenging for historical cities throughout Europe, wishing to find an optimal balance between the protection of the cultural heritage of the built environment and the improvement of its overall performance, in line with the EU Green Deal and New European Bauhaus. Energy retrofitting of historical buildings counts additional challenges due to the architectural restrictions, regulatory conditions, and costs given by the buildings' heritage value. Specifically, three main technical challenges are identified in the realization of energy retrofitting of historical buildings:

1. Technologies for the upgrading of buildings' envelopes have limited applications in heritage contexts. These solutions are mostly developed for modern buildings and their application in historical buildings may produce increased hygrothermal risks and potential damages. Moreover, heritage restrictions narrow down the range of possible technological solutions now available in the market.
2. Historical buildings used to be naturally ventilated and cooled, while the energy-efficiency upgrading of the buildings' envelopes typically reduces the air infiltration, and consequently the Indoor Air Quality (IAQ). Moreover, today's heating and

ventilation systems are typically not optimised for the architectural and physical characteristics of heritage buildings. Since typical heating systems in historical buildings relied on high-temperature spot systems (e.g. using fireplaces or stoves), they are not compatible with current low-carbon energy systems, which typically require lower temperatures to operate efficiently.

3. Options for renewable onsite systems are limited for heritage buildings, because of the heritage restrictions that limit the possibilities for their aesthetic integration and the limited availability of renewable sources in dense historical neighbourhoods.

Given the aim of HeriTACE to provide local authorities with a holistic and multi-scale Renovation Approach for heritage townhouses to bridge the gap between heritage restrictions and environmental ambitions, the process of defining a relevant KPIs assessment framework stemmed from reviewing proposed indicators from significant sources of information for further adaptation to the heritage context. The areas of applications of KPIs to be screened and evaluated were identified in relation to the overall ambition of HeriTACE. As illustrated in Figure 3 HeriTACE aims to develop and demonstrate a holistic renovation approach for heritage buildings by:

- Protecting their heritage value,
- Delivering healthy and comfortable environments
- Improving their energy-efficiency and their readiness to decouple from fossil fuels
- Increasing the on-site application of renewable and residual energy sources and their integration in the local energy grids.
- Reducing the renovation environmental impact by increased applications of material circularity,
- Increasing the effectiveness and affordability of renovations' life-time cost

To achieve this, HeriTACE holistic renovation approach integrates and optimises solutions at building's system and component level, at the building level, and at the neighbourhood level.

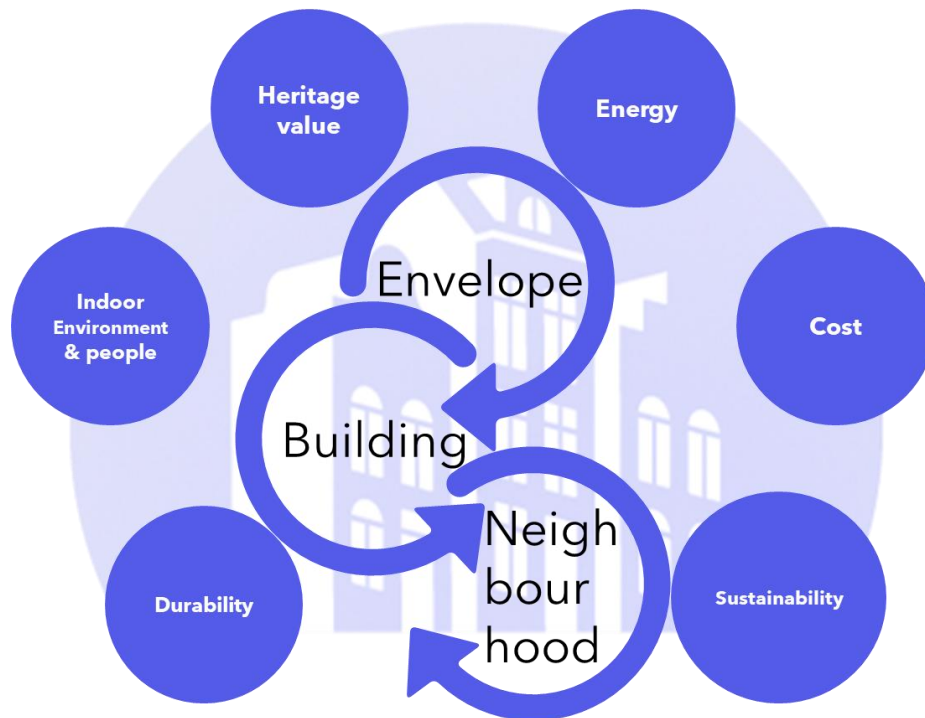


Figure 3. Concept of the holistic renovation approach of HeriTACE. Source: UGENT

Prompted by the holistic and multi-scale ambition of HeriTACE, relevant sources of information were screened in relation to their pertinence to building renovations in heritage contexts, users and occupants' satisfactions and comfort, cost saving, energy saving and environmental impact, and the integration of on-site renewable applications at neighbourhood level. In such a perspective, the most relevant sources of information examined include:

- EN 16883, for being the reference standard for energy retrofitting of historical buildings.
- EU FP7 H2020 EFFESUS, for its relevance of considering the evaluation of performance of energy retrofitting of historical buildings on multiple domains of assessment (energy, emissions, comfort, cost, heritage).
- EU Level(s), for being proposed as a framework of core indicators for the performance assessment of sustainability of new-build and major renovation projects.
- EU H2020 ARV, for its relevance of considering the evaluation of performance of energy retrofitting at neighbourhood level and including the renovation of a historical building as one of the case studies.

In addition, important indications for the definition of the HeriTACE KPIs assessment framework came from the context of the European Green Deal in general and in particular the Horizon funding call for the HeriTACE project. The expected outcomes defined in the funding call "Future-proofing historical buildings for the clean energy transition, HORIZON-CL5-2023-D4-01-02" specifically addressed reduction of energy demand, on-site construction waste, maintenance and lifetime renovation costs, and improvement of comfort, IAQ, smart readiness, and successful installation of renewable technologies, while preserving historical and cultural heritage values. These outcomes, later integrated in

HeriTACE as High Level Objectives, became the foundation for the definition of the assessment framework.

The HeriTACE High Level Objectives (HLOs) are defined as follows:

- HLO1. Develop a replicable holistic assessment model and standardised transdisciplinary processes to create a holistic vision and plan on the renovation requirements for heritage townhouses in historical neighbourhoods
- HLO2. Develop optimal and integrated design approaches for the deep renovation of heritage townhouses, reducing the overall building energy demand by 60%
- HLO3. Durable insulation and air tightness solutions for the renovation of building envelopes, respecting their heritage values and traditional building technology, with improved energy-efficiency by 60%.
- HLO4. Optimised and smart controlled HVAC-concepts optimising comfort and IAQ in historical townhouses precisely leading to a reduction of energy demands by 60%, by using smart design and control, and reduction of construction waste by 10% through minimal invasion and maximal reuse of existing components, and use of plug-and-play solutions. (HVAC & Control solutions)
- HLO5. Integrated R²ES-based energy supply solutions for heritage townhouses within historical neighbourhoods in three different climate zones, using 100% fossil-free energy sources in the building and neighbourhood and maximising the share of local R²ES-production at building and neighbourhood scale. With the aim of reducing energy demand by 15% and maintenance costs by 10%, and increasing the cost effectiveness by 10%.

Finally, the HeriTACE KPIs assessment framework is aligned with several EU policies and frameworks that call for decarbonisation, sustainability, affordability, and resource efficiency in the built environment. In particular, the assessment framework considers the Fit for 55, the Renovation Wave, the New European Bauhaus, Clean Energy for all Europeans, and the Sustainable Development Goals, with a specific focus on:

- SDG 7 (Affordable and Clean Energy).
- SDG 11 (Sustainable Cities and Communities).
- SDG 12 (Responsible Consumption and Production).
- SDG 13 (Climate Action).

2.2. Screening of relevant KPIs

The resulting screened KPIs are summarized in Table 1 and grouped according to Level(s) macro-objectives with some modifications. The Level(s) framework is based on 6 macro-objectives, describing the strategic priorities to be followed by the EU towards a carbon-neutral and sustainable built environment. These are identified as follows: 1) Greenhouse gas and air pollutant emissions along a building's lifecycle, 2) Resource efficient and circular material life cycles, 3) Efficient use of water resources, 4) Healthy and comfortable spaces, 5) Adaptation and resilience to climate change, 6) Optimized life cycle cost and values. To consider the project's specific building heritage context, a new grouping category is introduced (Heritage and Architecture), whereas the water-use category (macro-objective 3 in Level(s)) was removed from the list because not relevant to HeriTACE goals. KPIs from the identified sources were therefore grouped according to this initial list of categories, which were further refined in workshops carried out with the HeriTACE partners.

Table 1. Thematic areas and KPIs of the screened sources

	Level(s)	EFFESUS	EN 16883	ARV
Energy and environmental impact	Use stage energy performance - Life cycle Global Warming Potential	Lifecycle operational and embodied energy - Electrical and thermal energy use - Peak power demand - %RES - Lifecycle GHG emissions	Performance of operational energy demand - Lifecycle energy demand (renewable and non-renewable primary) - GHG emissions from measures implemented - Emissions of harmful substances	Non-renewable primary life cycle energy - Renewable energy ratio - Grid Delivered Factor - Net energy/net power - Flexibility index - Lifecycle GHG emissions - Air pollution from energy use
Resource use	Bill of quantities, materials and lifespans - Construction & demolition waste and materials - Use stage water consumption		Natural resource use	Materials from cycled sources - Reusability
Health and comfort of occupants	IAQ - Time outside of thermal comfort range - Lighting and visual comfort - Acoustics and protection against noise - Protection of occupier health and thermal comfort	IAQ - Thermal, visual, acoustic comfort	IEQ - Occupants' comfort	Dust and noise during retrofitting - Sufficiency and adequacy of space - Solar and daylight access - Accessibility - IAQ - Thermal comfort - Overheating risk - Acoustic comfort - Outdoor comfort
Adaptation and resilience	Design for adaptability and renovation - Design for deconstruction, reuse and recycling - Increased risk of extreme weather events - Increased risks of flood events		Reversibility - Influence on the use and users of the building - Ability of building users to manage and operate control systems	Flexibility and adaptability
Cost	Lifecycle cost - Value creation and risk exposure	ROI - CAPEX - OPEX - NPV - PDB - OPP - EPP	CAPEX - OPEX - ROI - NPV	Global Cost - Energy renovation rate - Number of jobs created - Construction time reduction

Heritage and architecture		Visual, physical, and spatial impact assessment - Fabric compatibility	Risk of material, constructional, structural, architectural, aesthetic, visual, and spatial impact - IEQ for building content and fabric preservation - Consequences of change of use and addition of new technical rooms - Technical compatibility of new materials	Aesthetics and visual qualities
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2.3. Criteria for KPIs definition

A series of physical and virtual workshops were held among the HeriTACE partners to identify the most relevant KPIs and define the foundation of the assessment framework. To begin with, the working group agreed in the Consortium Meeting in Trondheim on the identification of the thematic areas according to which the KPIs were going to be grouped. These were identified as such: Energy and Environmental Impact, Cost, Indoor Environmental Quality, and Heritage and Architecture. Such a division was deemed comprehensive to cover the goals described in the project's High Level Objectives. Accordingly, experts among the working group were assigned to each thematic area and virtual workshops were carried out subsequently for each thematic area to collaboratively discuss the selection of assessment categories and performance indicators. The workshops utilized a virtual blackboard to explore how different performance indicators could be applied across various aspects of the HeriTACE project, by identifying which HLOs they pertain to, the relevant metrics, the methods of calculation and measurement, and potential drawbacks and limitations. The activities carried out in the virtual workshops produced an initial proposal of definition for the assessment framework for each of the thematic areas. A final workshop held during the Consortium Meeting in Tallin helped finalize the identification of the relevant KPIs and define the assessment framework. In relation to the use of the assessment framework in the multi-dimensional assessment model, primary and secondary KPIs were identified. The division between primary and secondary KPIs was decided to streamline the procedure of performance assessment of the renovation scenarios. The aim was to identify primary KPIs to be used as proxy indicators of the renovation scenario performance, whereas the secondary KPIs to be used to provide additional information on the proxy indicator of the renovation scenario performance against the baseline. In summary:

- primary KPI: main proxy indicator for the performance assessment of renovation scenarios
- secondary KPI: additional and supporting indicator to the main proxy indicator.

The importance and weighting of the secondary KPIs against the primary KPIs in the process of evaluating the renovation scenarios will be discussed and detailed in the development of

the MDAM in Deliverable D5.7 due M36. However, a definition of the relationship between primary and secondary KPIs was already discussed and agreed upon in D5.5, as follows:

- the secondary KPIs described in Energy and Environmental Impact, IEQ, and Cost thematic areas are complementary to the respective primary KPIs. A weighting factor will be used to determine to what extent the performance of the renovation scenarios is modified by the analysis of these KPIs.
- the secondary KPIs described in Heritage and Architecture thematic area constitute the very essence of the corresponding primary KPI. This was decided because it was not found a single indicator that could fully represent the performance of the renovation scenarios with respect to this thematic area.

Figure 4 show a visual map of the discussion process (in this example, the Cost KPIs) held around the virtual blackboard. The starting point was the identification of outputs described in the project expected outcome and the identification of relevant KPIs that could capture the measurement of such outputs. Thereafter, description of the relevant methods for calculating the KPIs, the relative benchmark (whose detailed description is given in the reference scenarios, in Deliverable D5.4), limitations and issues at measuring and/or monitoring the proposed KPI, and finally, the proposed KPIs. The results of the blackboard workshops were then screened and refined during the physical workshops in Tallinn. The aim was to reach a definition of primary and secondary KPIs, their methods of calculation and ISO/EN standards of references (if relevant), limitations and rating of importance among the group of experts. The rating of importance was attributed by each expert (example of Heritage and Architecture KPI in Figure 5) as a test of evaluating weighting factors for the secondary KPIs.

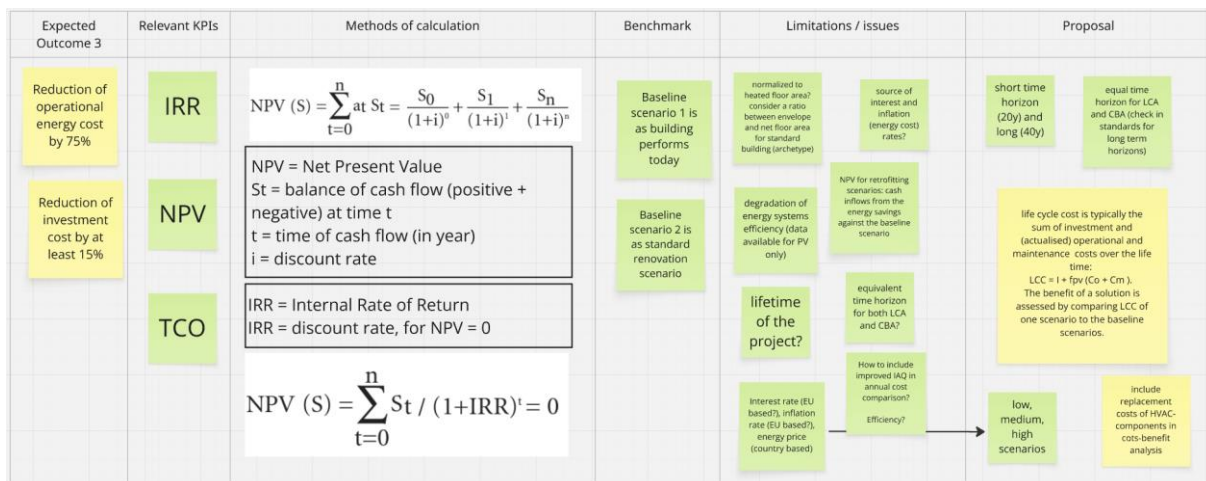


Figure 4. Snippet of the process of KPIs definition in the Cost virtual blackboard.

Heritage and Architecture KPIs	KPI name	Case study relevance (e.g. Heritace partner country / technological solution)	S = simulation M = measurement Q = questionnaire	Method / reference standard	Unit of measurement	Limitations / boundary conditions	Rating of importance (0-100)
Primary KPI	Heritage value compatibility			this is a container of the sub-KPIs, method of calculations will be defined later		building and neighbourhood	100
Sub-KPI 1	Technical compatibility Material compatibility -thermo-physical -Chemical -Biological -structural		S/M	Standards	threshold (to be defined). Output is Yes/No (depending of the distance of value from the threshold value)	building	100 (Alessia, Marta, Veerle, Cecilie) 80 (Ullar)
Sub-KPI 2	Durability • finishing layer ageing • construction decay		S/M	1. check with materials that are compatible with local climate/substrate (technical compatibility) 2. choose the one which is the longest lasting (years) evaluation based on past tests, experience.	years	building	100 (Ullar) 60 (Veerle, Alessia) 80 (Marta) 70 (Cecilie)
	Visual impact (now and in future - ageing) color proportion (in the element, in						80 (Veerle, Alessia)

Figure 5. Snippet of the process of final definition of Heritage and Architecture KPIs.

A summary of the primary and secondary KPIs is given in Table 2. More details on the method for using the primary and secondary KPIs in the performance evaluation of renovation scenarios is part of the development of the MDAM, and it will be described in Deliverable 5.7.

Table 2. List of KPIs to be used in the MDAM for the evaluation of the HeriTACE renovation scenarios

KPI	Energy and Environmental Impact	Cost	IEQ	Heritage and Architecture
Primary KPI	Primary Energy Use	Global Cost	Thermal comfort	Heritage value compatibility
Sub-KPI 1	Energy Use	CAPEX	IAQ	Technical and material compatibility
Sub-KPI 2	Energy Delivered	OPEX	Overheating	Durability
Sub-KPI 3	Heating/Cooling peak power	Cost of CO2 saving	Relative Humidity	Visual Impact
Sub-KPI 4	Share of renewable and residual energy source	Cost of primary energy saving		Spatial Impact
Sub-KPI 5	Operational GHG emissions	Payback time		Share of construction / demolition volume
Sub-KPI 6				Impact on authenticity
Sub-KPI 7				Reversibility

3. KPIs calculation methods

This chapter describes the methods for calculating the KPIs defined according to the four thematic areas of impact (Energy and Environmental Impact, Cost, IEQ, Heritage and Architecture). As mentioned in the previous chapter, the list proposed in this report will be revised and refined after testing the KPIs in the application of the MDAM in the renovation scenarios.

3.1. Energy and Environmental Impact KPIs

Energy and Environmental Impact KPIs are connected to the project call's expected outcomes 1 and 6, and to HeriTACE HLOs 2, 3, 4, and 5. The project call's expected outcomes 1 and 6 are the followings:

- Reduction of energy demand by at least 60%, preserving historical heritage values
- Where possible, increased potential of successful installation of R²ES, and improvement of smart readiness, in a way that respect the specificities of historical buildings.

Definitions of energy KPIs and boundary conditions are retrieved from the standard ISO 52000-1: Energy performance of buildings - overarching EPB assessment. Figure 6 describes the boundary conditions for each of the energy definition according to the standard ISO 52000-1. Energy losses due to energy transformation and transportation inefficiencies occur at the boundaries between each energy use stage.

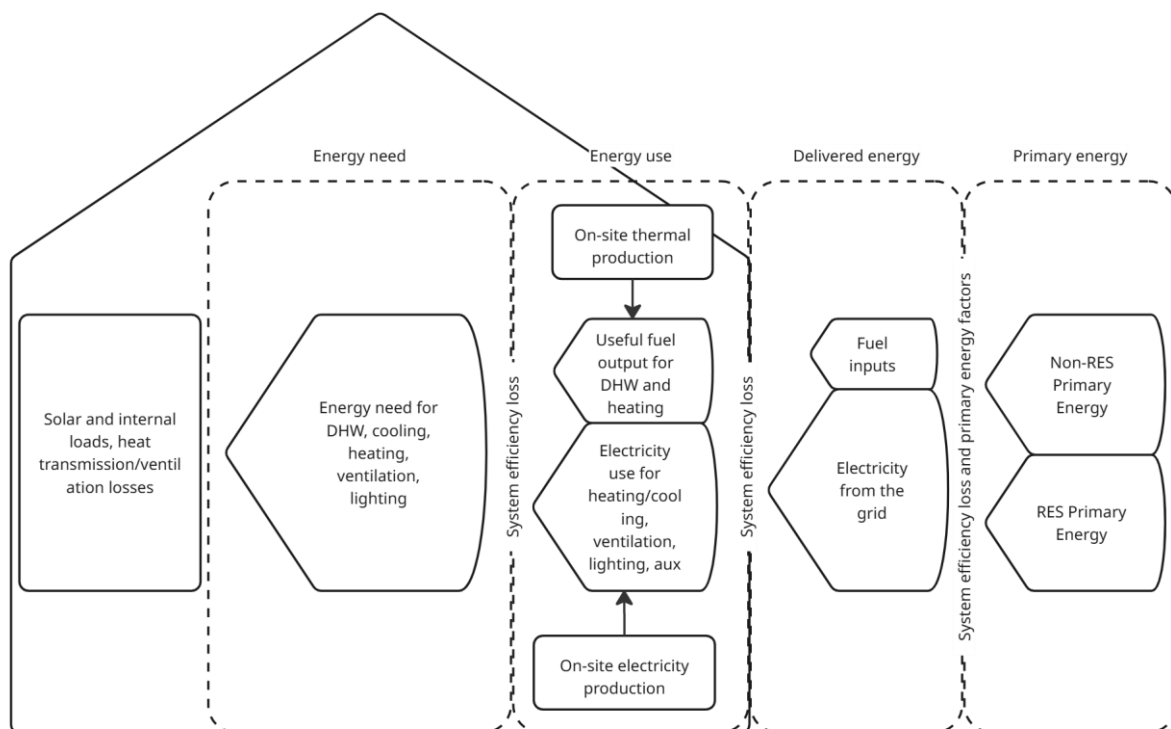


Figure 6. Scheme of boundary conditions according to ISO 52000-1

Primary energy use

Primary energy is defined as the energy that has not been subjected to any conversion or transformation process and includes both non-renewable and renewable energy. To calculate the primary energy use, Primary Energy Factors (PEF) are needed. These describe the amount of total primary energy (from renewables, PEF_{ren} and from non-renewables, PEF_{nren}) is used to generate a unit of final energy and are expressed in kWh/m²/year of conditioned floor area of building, as follows:

$$TPEF_{grid} = PEF_{nren} + PEF_{ren}$$

Where $TPEF_{grid}$ is the Total Primary Energy Factor of the energy distribution network, calculated as the sum of non-renewable (PEF_{nren}) and renewable (PEF_{ren}) energy factor. PEFs, especially those for electricity generation and district heating/cooling, are dependent on country-specific energy mixes, which are advisable to be used. Default values are included in the ISO 52000, shown in Table 3.

Table 3. List of renewable and non-renewable PEF, according to ISO 52000.

	PEF_{nren}	PEF_{ren}	TPEF
Fossil fuel – solid	1.1	0	1.1
Fossil fuel – liquid	1.1	0	1.1
Fossil fuel – gaseous	1.1	0	1.1
Bio-fuel – solid	0.2	1	1.2
Bio-fuel – liquid	0.5	1	1.5
Bio-fuel – gaseous	0.4	1	1.4
District heating	1.3	0	1.3
District cooling	1.3	0	1.3
Solar (electric)	0	1	1
Solar (thermal)	0	1	1
Wind	0	1	1
Geo-, aero-, hydrothermal	0	1	1
Electricity	2.3	0.2	2.5

Primary energy use is therefore calculated as the sum of units of delivered energy per energy carrier (e.g. electricity, gas, oil, etc.) multiplied by the corresponding PEF, as follows:

$$E_{prim} = \sum_i (E_{del,i} * PEF_i)$$

Where E_{prim} is the Primary energy use expressed in kWh/m² year of heated floor area, $E_{del,i}$ is the delivered energy from energy carrier i (electricity, gas, etc.) expressed in kWh/m² year of heated floor area, and PEF_i is the primary energy factor for energy carrier i (defined nationally or in ISO 52000).

The evaluation of the Primary energy use KPI is performed by comparing the ratio of primary energy use between the HeriTACE renovation scenario i and the baseline.

Energy use

Energy use is defined as the energy fed into a technical building system to satisfy an energy need. In the context of EN 15316 refers to the total energy consumed by building technical systems (such as heating and domestic hot water systems) including all internal losses and

auxiliary consumption, and may include on-site produced energy to meet the required energy needs. The general formula for energy use (E_{use}) is:

$$E_{use} = Q_{need} + \text{System Losses} + \text{Auxiliary Energy}$$

Or, more specifically, for a heating system:

$$E_{use} = Q_{need} + Q_{loss,emission} + Q_{loss,distribution} + Q_{loss,storage} + W_{aux}$$

Where Q_{need} is the energy need for the service (e.g., heating or hot water), $Q_{loss,emission}$ represent the losses in the emission sub-system (e.g., radiators), $Q_{loss,distribution}$ are the losses in the distribution sub-system (e.g., pipes), $Q_{loss,storage}$ are the losses in the storage sub-system (e.g., hot water tanks), and W_{aux} is the auxiliary energy use (e.g., for pumps, fans, controls). All parameters are expressed in kWh/m² year of heated floor area. The evaluation of the Energy use KPI is done by calculating the ratio between the energy use of the renovation scenario i and that of the baseline.

Energy need

According to EN-15316: The *energy need* (sometimes referred to as "heat need" or "energy requirement") is the amount of energy required to maintain the desired indoor conditions (such as temperature) in a building, before considering any losses or system inefficiencies. It represents the theoretical demand for heating, cooling, or domestic hot water needed by the building occupants or processes. The energy need for a service (e.g., heating) is calculated as:

$$Q_{need} = \sum_t [Q_{loss,t} - Q_{gain,t}]$$

Where Q_{need} is the energy need (e.g., for heating) over the calculation period, $Q_{loss,t}$ represents the heat losses (transmission + ventilation) during time step t , and $Q_{gain,t}$ are the internal (from occupants and equipment) and solar gains during time step t . All parameters are expressed in kWh/m² year of heated floor area. The evaluation of the Energy need KPI for a HeriTACE renovation scenario i is done by calculating the ratio of energy need between the renovation scenario and the baseline.

Energy Delivered

According to EN-15316: Energy delivered (also called "delivered energy" or "net energy") is the energy supplied by technical building systems to meet the required services (heating, cooling, hot water, etc.) at the system boundary of the building, nearby, and distant (from external sources, e.g., from the electricity grid, gas network, or district heating). This value takes into account recoverable losses or gains, meaning it reflects the actual energy input to the building's systems after considering system performance and losses.

$$E_{del} = \frac{Q_{need}}{\eta_{sys}}$$

Where E_{del} is the energy delivered to the building (e.g., by boilers, heat pumps, etc.), and Q_{need} is the Energy need (defined in 3.1.3), both expressed in kWh/m² year, η_{sys} is the overall efficiency of the technical system (including generation, distribution, emission), calculated as follows:

$$\eta_{sys} = \eta_{gen} * \eta_{dist} * \eta_{em}$$

Where η_{gen} is the efficiency of energy generation system, η_{dist} is the efficiency of the energy distribution system, and η_{em} is the efficiency of the energy emission system. If there are multiple energy carriers or systems, their efficiency will be summed. The calculation of the performance of a HeriTACE renovation scenario i is given by the ratio of the energy delivered between the renovation scenario and the baseline.

Heating/cooling peak power

Heating/Cooling Peak Power is the maximum output required by the heating or cooling system to maintain specified indoor conditions, determined by the most demanding (design) load calculated for a given time interval (such as hourly) under the most severe conditions relevant for the building site. ISO 52016-1:2017 specifies the calculation of design heating and cooling loads based on hourly intervals, using outdoor climate data that represent the most demanding (extreme) conditions for the location and intended use, but does not prescribe a single value for "extreme" outdoor temperature—this is typically set by national regulations. The standard includes all relevant heat and moisture loads (from transmission, ventilation, infiltration, internal gains, and solar gains) in the calculation of these peak loads.

Internal gains are the heat (and sometimes moisture) generated inside the building by occupants, lighting, appliances, and other equipment. These are considered in the calculation of heating and cooling needs, as they reduce the amount of external energy required for space conditioning.

Share of renewable and residual energy source

According to EN ISO 15316 the share of renewable energy source refers to the proportion of the total energy used by a building or system that is supplied from renewable energy sources (such as solar, wind, biomass, geothermal, or ambient energy). For residential buildings, typical end-uses include: space heating, space cooling, domestic hot water, lighting, ventilation and appliances and other electrical loads.

This share is calculated as the ratio of the renewable energy delivered to the building or system to the total delivered energy, expressed as a percentage.

$$\text{Share of renewable energy (\%)} = \frac{\text{Delivered renewable energy}}{\text{Total delivered energy}} \times 100$$

To calculate the delivered renewable energy for a building or system, how much energy is supplied to the building from renewable sources must be determined. The calculation method depends on the technology. The examples for a heat pump and a PV system are explained below, using the logic of EN ISO 15316 and related EPB standards.

Heat pump example

A heat pump extracts renewable ambient heat (from air, ground, or water) and delivers it to the building as useful heat. The calculation of delivered renewable energy for a heat pump is based on the share of the heat output that is considered renewable.

$$\text{Delivered renewable energy (heat pump)} = \text{Total heat output} \times \text{Renewable fraction}$$

The renewable fraction is typically defined as the part of the heat output that is not attributed to the input of non-renewable electricity or fuel. For example, if the heat pump has a coefficient of performance (COP) of 3, then for every 1 kWh of electricity consumed, 3 kWh of heat are delivered. The renewable fraction is considered as the difference between the total heat output and the input of non-renewable energy (if using grid electricity with a defined primary energy factor).

However, EN ISO 15316 and the EPB standards generally treat the electricity input as non-renewable unless it is specifically from a renewable source (like on-site PV). The renewable share for a heat pump is thus often considered as the difference between the total heat delivered and the non-renewable primary energy input, but this depends on national regulations. In many EU countries, the calculation is:

$$\text{Delivered ren. energy (heat pump)} = \text{Heat output} \times \frac{\text{Renewable energy factor (from ambient source)}}{\text{COP}}$$

But in practice, the standard often uses the total heat output as "delivered energy" and the renewable share is calculated separately for the building's overall energy balance, based on primary energy factors and national rules. For a simple example, if a heat pump delivers 10 000 kWh of heat per year, and national rules consider 60% of this to be renewable (based on the ambient source), then:

$$\text{Delivered renewable energy} = 10\,000 \times 0.6 = 6\,000 \text{ kWh/year}$$

The exact method and renewable fraction are set by national or regional regulations, not by EN ISO 15316 alone.

PV system example

A photovoltaic (PV) system generates electricity from solar energy, which can be used directly in the building or exported to the grid.

Delivered renewable energy is simply the amount of PV-generated electricity that is consumed and stored in on-site battery systems by the building (on-site use), not exported.

Operational GHG emissions

Describes the GHG emissions (as kgCO₂ equivalent) of energy use of renovation scenarios, to be calculated according to EN 15978. The standards specify the energy end-uses included in the calculation, which are: heating, DHW, cooling, humidification/dehumidification, ventilation, lighting, auxiliary energy (pumps, control, automation). Energy-to-CO₂ emissions conversion factors of typical fuels are given in Annex E of EN 15603. Electricity-to-Co₂ emissions conversion factors of national electricity grids are reported according to latest data from the EC Joint Research Centre.

Additional performance indicators

Table 4 provides a list of additional performance indicators (PIs) that are used in HeriTACE to evaluate the effectiveness of the renovation scenarios and technological solutions against the baseline. These PIs are not used in the MDAM for the overall assessment of the renovation scenarios.

Table 4. List of additional PIs relevant to the evaluation of energy systems. These are not used in the evaluation process of the MDAM.

Name	Short description
Ventilation losses (EN ISO 52016-1)	Describes the heat ventilation losses through the building envelope and ventilation system.
Transmission losses (EN ISO 52016-1)	Describes the heat transmission losses through the external building envelope due to temperature difference between inside and outside
U-value (EN ISO 6946)	Describes the thermal transmittance of a building component, measured in $W/(m^2 \cdot K)$. It quantifies how much heat is lost through a given area of a building element per degree of temperature difference.
Supply temperature (EN ISO 15316)	Describes the temperature of fluid (e.g. air, water, etc) in the energy distribution system.
Energy use per person	Describes the normalization of energy use per number of occupant (instead of heated floor area), to account for the effective use of building space.
Energy production efficiency (EN ISO 15316)	Describes the efficiency of energy transformation (e.g. solar to electric) in energy generation system
Energy system efficiency (EN ISO 15316)	Describes the overall efficiency of the energy system (detailed in chapter 3.1.4)
Auxiliary energy use (EN ISO 15316)	Describes the energy use for pumps, fans, controls, etc, detailed in chapter 3.1.2
Heating-to-cooling ratio	Describes the annual heating demand/annual cooling demand (for storage optimisation and system sizing)
Demand overlap coefficient	Measure of the temporal match between the heating demand and cooling demand

3.2. Cost KPIs

Cost KPIs are connected to the project call's expected outcomes 3 and 5, and to HeriTACE HLO 5. The project call's expected outcomes 3 and 5 are the followings:

- Improved lifetime renovation cost effectiveness compared to conventional renovation.
- Significant reduction in maintenance costs.

Definitions of cost KPIs and calculation methods are derived and adapted from the standard EN 15459-1: Energy performance of buildings. Economic evaluation procedures for energy systems in buildings, and from the (EU) No 244/2012

Total Cost of Ownership

Total Cost of Ownership (TCO), referred as Global Cost in the EU 244/2012, helps to select the most cost-effective renovation scenario in a life cycle perspective, taking into account construction, operation, maintenance, replacement and end-of-life cost and value. In the energy retrofitting design phase, TCO helps in the selection of alternatives with the lowest/optimal global costs. In the evaluation of energy retrofitting scenarios, the GC allows the comparison before and after the intervention.

The TCO of the Heritage renovation scenarios is calculated as the sum of different types of costs evaluated for a calculation period. TCO calculation considers the costs occurring at

the building's lifecycle Stage A (production and construction process), Stage B (operation and maintenance), and Stage C (end of life), as follows:

$$TCO = \sum C_a + \sum C_b + \sum C_c + \sum C_d + \sum C_e$$

Where C_a is the one-time initial investment cost, C_b is the annual operation and maintenance cost, C_c is the annual cost of utilities (e.g. energy use), C_d is the cost for future renovation/replacement of building components, C_e is the cost (residual value) at the building/building component end of service life. Annualized cost will be calculated by considering the actual monetary value at the time of the calculation. This is performed by multiplying the annual cost by a discount factor, as follows:

$$R_d(p) = \left(\frac{1}{1 + r/100} \right)^p$$

Where $R_d(p)$ is the discount factor, p is the number of years from the starting of the calculation period t , and r is the real interest rate. The real interest rate is the nominal interest rate (advertised by national banking institutions) adjusted for inflation, representing the true gain or loss in purchasing power for the money lender or borrower. The real interest rate is calculated as follows:

$$\text{Real interest rate} = \text{nominal interest rate} - \text{inflation rate}$$

TCO is expressed in either EUR/unit of building component or technical installation or EUR/m² of conditioned floor area. The calculation period is set to 30 years. The real discount rate and inflation rate of goods and services (including the energy price) are based on national values.

CAPEX

Initial investment costs C_a are all costs incurred up to the point when the renovated building or the building element is delivered to the customer, ready to use. These costs include design, purchase of building elements, connection to suppliers, and installation. These are expressed in either EUR/unit of building component or technical installation or EUR/m² of conditioned floor area.

OPEX

Annual operative costs C_b and C_c are the sum of running costs and periodic costs or replacement costs paid at year i . Running costs are the sum of annual maintenance costs, operative costs, and cost for utilities (operative energy use). Replacement cost C_d is the substitute investment for a specific building element, according to its estimated lifespan during the calculation period. Operative costs and replacement costs are expressed in either EUR/unit of building component or technical installation or EUR/m² of conditioned floor area. Reduced annual maintenance cost (C_b) of renovation scenarios can be evaluated by considering its ratio between the baseline and the renovation scenario. According to HLO 5, a target 10% reduction is sought in the project.

Cost of CO₂ reduction

Cost of CO₂ reduction is calculated to evaluate the environmental cost effectiveness of the energy retrofitting scenario j against either the baseline (pre-renovation scenario) or another energy retrofitting scenario n . This is calculated as the ratio of TCO of energy

retrofitting scenario j to the difference of the operative CO₂ emissions of scenario j and the operative CO₂ emissions of either the baseline or scenario n , as follows:

$$CR_{CO_2,j}(t) = \frac{TCO_j(t) - TCO_n(t)}{CO_{2,n}(t) - CO_{2,j}(t)}$$

Where $CR_{CO_2,j}$ is the cost of CO₂ reduction of energy retrofitting scenario j , t is the calculation period, TCO_j is the Total Cost of Ownership of energy retrofitting scenario j , $CO_{2,n}(t) - CO_{2,j}(t)$ is the difference between the operational emissions of baseline n and scenario j . This is expressed in EUR/kgCO₂.

Cost of PE savings

Similarly to the cost of CO₂ reduction, the cost of Primary Energy (PE) savings of scenario j is calculated as follows:

$$CR_{PE,j}(t) = \frac{GC_j(t) - GC_n(t)}{PE_n(t) - PE_j(t)}$$

This is expressed in EUR/kWh.

Payback period

Payback Period (PP) is the time when the investment costs are balanced with the monetary savings occurring in the calculation period. This is calculated as the ratio of the investment cost to the average annual cost savings and expressed in years, as follows:

$$PP_j = \frac{C_{a,j} - C_{a,n}}{(C_b + C_c + C_d)_{avg,n} - (C_b + C_c + C_d)_{avg,j}}$$

Where PP_j is the payback period of renovation scenario j , $C_{a,j}$ is the investment cost of renovation scenario j , $C_{a,n}$ is the investment cost of baseline, $(C_b + C_c + C_d)_{avg,n} - (C_b + C_c + C_d)_{avg,j}$ is the difference of average annual operative costs and replacement costs between baseline and renovation scenario j .

Increase of property value

The increase of property value is defined as additional PI and not included in the KPI framework of the MDAM. Two possible methods for calculating this PI are discussed:

- An appreciation index, which is used as multiplier of the property value before renovation. Such an index is country specific.
- A decision tree with multiple datapoints. The building is characterized by several labels (e.g. number of rooms, insulation level, type of glazing, etc) and a price. At the end side of the decision tree, the price difference of different buildings can be compared with respect to variation of single label (e.g. insulation level). This allows to assess variation of property value before and after renovations by pinpointing the effect of single parameters.

The decision of using either the first or second methods considered in relation to availability of data in the project partner countries.

3.3. IEQ KPIs

Indoor Environmental Quality (IEQ) KPIs are connected to the project call's expected outcome 4 and to HeriTACE HLO 4. According to the project's call expected outcome 4, project results are expected to contribute to improved comfort, Indoor Air Quality and Indoor Environmental Quality.

Definitions of IEQ KPIs and calculation methods are derived and adapted from national building regulations and European standards. The following sources of national regulations and standards regarding comfort of buildings' occupants are used: EN 16798-1:2019, ISO 13790:2008, ISO 7730, and in addition TEK17 for Norway, and Presidential Decree (DPR) n. 74 (2013) and Decree n. 383 (2022) for Italy.

Thermal comfort

Calculation methods and recommended values for thermal comfort are derived from the EN 16798-1. The standard specifies requirements for indoor environmental parameters for thermal environment, indoor air quality, lighting and acoustics and methods for definition of such parameters for building system design and energy performance calculations. The document sets four levels of IEQ categories, based on the level of expectations by the occupants, ranging from CAT I (high) for building with occupants with special needs to CAT IV (low) where discomfort is expected. CAT II (medium) is considered when a "normal" level of comfort is expected by the occupants.

The standard provides design values and recommendations for building with either mechanical heating/cooling systems or without. Table 5 shows the design operative temperatures in buildings with mechanical heating/cooling systems and CAT II level of comfort expectation, assuming 50% relative humidity, low air velocity (<0.1 m/s), and normal clothing level in winter (clo 1.0) and light clothing level in summer (clo 0.5).

Table 5. Design operative temperatures (T_o) for buildings with mechanical heating/cooling and CAT II level of comfort expectations.

	Minimum T_o in heating season (°C)	Maximum T_o during cooling season (°C)
Residential		
Bedrooms, kitchen, living spaces (sedentary activity 1.2 MET)	20	26
Utility rooms, storage, other spaces (standing/walking 1.5 MET)	16	-
Offices, restaurants, auditoriums, and similar buildings		
Sedentary activity (1.2 MET)	20	26

When a mechanical heating/cooling system is not installed in the building, the standard provides a calculation method of recommended operative temperature ranges taking into account the opportunities for the occupants to adapt to the indoor thermal environment. Table 6 shows the ranges of operative temperatures (T_o) for buildings without mechanical heating/cooling systems, CAT II of comfort level expectations and the following assumptions:

- low air velocity (<0.1 m/s)
- normal clothing level in winter (clo 1.0) and light clothing level in summer (clo 0.5).

- 40% relative humidity in winter, and 60% relative humidity in summer.

Table 6. Ranges of operative temperature (T_o) for buildings without mechanical heating/cooling and CAT II level of comfort expectations.

	Range of T_o in heating season (°C)	Range of T_o during cooling season (°C)
Residential		
Bedrooms, kitchen, living spaces (sedentary activity 1.2 MET)	20-25	23-26
Utility rooms, storage, other spaces (standing/walking 1.5 MET)	16-25	-
Offices, restaurants, auditoriums, and similar buildings		
Sedentary activity (1.2 MET)	20-24	23-26

Recommended ranges of indoor operative temperature are derived as function of the outdoor running mean temperature, as follows:

$$T_{o,CAT II,upper} = 0.33T_{rm} + 18.8 + 3$$

$$T_{o,CAT II,lower} = 0.33T_{rm} + 18.8 - 4$$

Where: $T_{o,CAT II,upper}$ is the upper limit of operative temperature for CAT II building (°C), $T_{o,CAT II,lower}$ is the lower limit of operative temperature for CAT II building (°C), T_{rm} is the outdoor running mean temperature (°C). National regulations define specific parameters for the definition of comfort standard which may differ from those defined in the EN 16798-1, as shown in Table 7.

Table 7. Definition of indoor thermal comfort according to national regulations of the HeriTACE partner countries with case studies,

Country	Specifications	Reference
Estonia	CAT I-III	EVS-EN 16798-1:2019
Belgium	CAT I-IV, different climatic zones for Brussels, Flanders and Wallonia	EN 15251
Italy	Heating set point T_o 19 + 2 °C Cooling set point T_o 26 - 2 °C Different climatic zones for allowed daily hours of heating (From 6 h/day in A to 24 h/day in F)	DPR 74 (2013) Decree 383 (2022) DPR 412 (1993)
Norway	For CAT II-III Heating set point T_o 19-24 ± 2 °C Cooling set point T_o 23 ± 1 °C	NS-EN 15251

The evaluation whether the indoor thermal conditions meet the required building category (CAT II) is performed by considering the number of hours the environmental parameter (operative temperature) fall within the design range. Table 8 shows the maximum allowable deviation of hours falling outside the design range defined in building CAT II.

Table 8. Ranges of allowable deviations expressed as % of total hours in week, month, and year.

	Weekly range of deviation		Monthly range of deviation		Yearly range of deviation	
Min/max % of allowable hours outside range (T_o)	20%	50%	12%	25%	3%	6%

The evaluation of the Thermal comfort KPI is performed by comparing the % of deviation of total time from CAT II temperature range between the HeriTACE renovation scenario and the baseline, where a smaller deviation means an improved thermal comfort, as follows:

$$TC_{ren.scen\ i} = \frac{Dev.CAT\ II_{ren.scen\ i}}{Dev.CAT\ II_{base}}$$

Where $TC_{ren.scen\ i}$ is the improvement of thermal comfort in the HeriTACE renovation scenario i expressed as %, $Dev.CAT\ II_{ren.scen\ i}$ is the deviation of hours of operative temperature falling outside CAT II boundaries, expressed as %, $Dev.CAT\ II_{base}$ is the deviation of hours of operative temperature falling outside CAT II boundaries, expressed as %.

Indoor Air Quality (CO₂ concentration)

Carbon dioxide (CO₂) is a colourless and odourless gas which at concentration between 350-450 ppm is a natural component of ambient air. It is a waste product of metabolism and consequently can be used as tracer for human activity and occupancy in building spaces. An increase of CO₂ concentration in the indoor air is likely due to either presence of many persons in a relatively small space or poor ventilation in buildings, where presence of few occupants can lead to increase of CO₂ concentration to uncomfortable levels. The European Collaborative Action (ECA) derived a model of occupants' dissatisfaction based on concentration of CO₂, showing 20% of occupants' dissatisfaction (Percentage Person Dissatisfied, PPD) at 1 000 ppm and above.

EN 16798-1:2019 and EN 16798-2:2019 provide design values of CO₂ concentration above outdoors for demand-controlled ventilation systems in residential spaces (living rooms and bedrooms). Lower and upper boundaries of CO₂ concentrations are defined for each building category, assuming CAT II equals to 20% of expected dissatisfied occupants. Table 9 shows CO₂ ppm concentration above outdoors level (set to 400 ppm) as design value for mechanical ventilation systems in CAT II.

Table 9. CO₂ concentrations in residential spaces.

Category	Design CO ₂ concentration (ppm above outdoors) for sedentary activities.	
	Living rooms	Bedrooms
I	550	380
II	800	550
III	1350	950
IV	>1350	>950

Indoor Air Quality (IAQ) in the HeriTACE renovation scenarios is evaluated by considering the CO₂ level as an indicator of satisfactory ventilation rates. Measurements of CO₂ levels

are carried out in the pre-renovation buildings (baseline). Average of measured CO₂ concentrations during occupied time in the baseline are then used to define the IAQ category the baseline belongs to, calculated on the time-integrated concentration of CO₂ in respective categories, as shown in Table 10.

Table 10. Ranges of allowable deviations expressed as % of total hours in week, month, and year.

	Weekly range of deviation		Monthly range of deviation		Yearly range of deviation	
Min/max % of allowable hours outside range (T _o)	20%	50%	12%	25%	3%	6%

Equivalent ventilation rates in the baseline are derived from the IAQ category according to EN 16798-1:2019 (Table 11).

Table 11. Design ventilation air flow rates for building categories.

Category	Total design ventilation air flow rate for sedentary activities.	
	l/s person	l/s m ²
I	20	2
II	14	1.4
III	8	0.8
IV	5.5	0.55

The evaluation of the IAQ KPI is performed by comparing the % of deviation of CO₂ concentration from the CAT II set for bedroom and living room. To estimate the exposure effect to higher-than-recommended concentration levels of CO₂, the deviation from recommended limits is weighted over time. Therefore, hourly calculation of the CO₂ level are performed for each of the room categories, the distance from the upper limit is calculated for every hour, and the total sum of the deviation/hours (as ppm/h) is derived. The performance of the renovation scenario against the baseline is calculated for each room category as follows:

$$IAQ_{ren.scen\ i} = \frac{Dev.CAT\ II_{ren.scen\ i}}{Dev.CAT\ II_{base}}$$

Where $IAQ_{ren.scen\ i}$ is the improvement of IAQ in the HeriTACE renovation scenario i expressed as %, $Dev.CAT\ II_{ren.scen\ i}$ is the deviation of hours of CO₂ concentration falling outside CAT II boundaries for each room category, expressed as %, $Dev.CAT\ II_{base}$ is the deviation of hours of Co₂ concentration for corresponding room category falling outside CAT II boundaries, expressed as %.

Overheating

Overheating in buildings is expected to be more intense and prolonged due to the current rate of climate change and global warming. Recent studies have shown that the frequency and duration of heatwaves have increased in every region of the world, since the 1950s . Indoor overheating significantly deteriorates the occupants' comfort, productivity, well-being, and health. Calculation of overheating in built environment is considered in several building regulations across the EU. Table 12 shows overheating indicators used in the HeriTACE partner countries. Estonia and Norway uses an overheating index based on

amount of hours exceeding a defined temperature limit. Belgium (in Flanders and Wallonia) uses a time-integrated overheating index based on monthly values, whereas Italy does not use a specific overheating index but relies on operative temperature defined for climatic zones. Table 12 shows the overheating indicators used in the HeriTACE partner countries with case studies.

Table 12. Overheating indicators in HeriTACE partner countries

Estonia	Hours of exceedance of the indoor temperature 150 Kh > 27C in residential buildings 100 Kh > 25C in non-residential buildings
Belgium	Monthly overheating index 1000 Kh < I_{overh} < 6500 Kh
Italy	No overheating threshold, but only operative temperature. possible to refer to EN 16798-1 (Upper limit for CAT II) $t_{o,CAT II} = 0.33t_{rm} + 18.8 + 3$
Norway	Hours of exceedance of the outdoor temperature 50 h > 26C in residential and commercial buildings

To set a coherent method for calculating the overheating index across the HeriTACE partner countries, the recommendation from the EN 16798-2 is used. The degree hours method (or method B, as in the standard) defines the overheating index as the time during which the actual operative temperature exceeds the specified range during the occupied hours. The time exceedance is weighted by a factor which is dependent on the extent in degree of the exceedance, as follows:

$$Wf = 0 \quad \text{for} \quad T_{o,lower,CAT II} \leq T_o \leq T_{o,upper,CAT II}$$

Where $T_{o,lower,CAT II}$ refers to the lower limit for operative temperature of such category, equal to 23 °C, $T_{o,upper,CAT II}$ is the upper limit for same category, equal to 26 °C, and T_o is the operative temperature in either the baseline or the HeriTACE renovation scenario i . The weighting factor Wf for overheating is calculated as follows:

$$Wf = T_o - T_{o,upper,CAT II}$$

The overheating exceedance degree-hours are calculated by integrating over time the weighting factor for when the operative temperature is above the CAT II upper limit, as follows:

$$\sum Wf \cdot \text{time} \quad \text{for} \quad T_o > T_{o,upper,CAT II}$$

The evaluation of the overheating KPI between the HeriTACE scenario i and the baseline is performed by comparing the ratio of the exceedance degree-hours between these two as follows:

$$OVH_{ren.scen i} = \frac{Exc. CAT II_{ren.scen i}}{Exc. CAT II_{base}}$$

Where $OVH_{ren.scen i}$ is the improvement of overheating reduction in the HeriTACE renovation scenario i expressed as %, $Exc. CAT II_{ren.scen i}$ is exceedance degree-hours of operative

temperature in HeriTACE renovation scenario i falling above CAT II upper limit, $Exc.CAT II_{base}$ is exceedance degree-hours of operative temperature in the baseline falling above CAT II upper limit,

Relative Humidity

The last IEQ KPI to be considered in the evaluation of HeriTACE renovation scenarios is relative humidity level. The EN 16798-1:2017 standard provides recommended design values for humidification/dehumidification systems in spaces where humidity levels are set by human occupancy. These are set to 60% RH for dehumidification and 25% RH for humidification for a CAT II building. Such values may differ if buildings or spaces have a use different from residential, such as museums, archives, art galleries, etc. The evaluation of this KPI is performed by considering the deviation over time of indoor RH from ideal 30-70% RH. Plotted hourly deviations are then multiplied by a weighing factor representing the hourly reported distance from the upper (70% RH) and lower (30% RH) ideal range. The KPI performance is evaluated by the ratio of hourly weighted deviations between the renovation scenario and the baseline.

Additional performance indicators

Table 13 provides a list of additional performance indicators (PIs) that are used in HeriTACE to evaluate the effectiveness of the renovation scenarios and technological solutions against the baseline. These PIs are not used in the MDAM for the overall assessment of the renovation scenarios.

Table 13. Additional PIs not included in the MDAM.

Name	Short description
Disability-adjusted life-year (DALY)	Describes the chronic harm caused by airborne contaminants and identify the most harmful (PM _{2.5} , PM _{10-2.5} , NO ₂ , formaldehyde, radon, and O ₃)
Standard Effective Temperature (SET)	Describes the equivalent dry bulb air temperature of an isothermal environment at 50 % relative humidity and still air for standardized clothing level in accordance to activity concerned.
Heat Index (HI)	Describes temperature feeling by combining relative humidity with air temperature.
Wet Bulb Globe Temperature	Describes the sum of linear weighting of air, black globe and naturally ventilated web bulb temperatures.
Indoor Overheating Degree (IOD)	Describes the hourly summation over the summertime period of the positive values of the difference between the operative temperature of the occupied building thermal zones and the zonal thermal comfort limit temperature, divided by the sum of the zonal occupied hours.
Ambient Warmness Degree (AWD)	Describes the hourly summation over the summertime period of the positive values of the difference between the outdoor air temperature and a fixed base temperature.
Overheating Escalation Factor (OEF)	Describes the ratio of IOD to AWD

3.4. Heritage and Architecture KPIs

Heritage and Architecture KPIs are used in HeriTACE as means to evaluate the performance of the energy retrofitting scenarios with respect to the preservation of the buildings' heritage values. Given the complexity of identifying appropriate KPIs, it was decided to rely on the evaluation framework described in the EN 16883:2017 for defining a starting ground of KPIs selection. The list suggested in the standard was further adapted to match the characteristics of HeriTACE renovation scenarios and the overall KPI assessment framework. In such a perspective, some of the indicators mentioned in the standard, such as those covering, energy, IAQ, and cost performance, were excluded from the Heritage and Architecture KPIs list since these are already considered in the other thematic areas, previously described in this report. Other indicators were merged into a single KPI. More details are given in the table 14:

Table 14. List of EN 16883 indicators and corresponding HeriTACE KPIs.

EN 16883:2017 indicators	Corresponding HeriTACE KPIs	Motivation of change
Technical compatibility: Hygrothermal risk Structural risk Corrosion risk Salt reaction risk Biological risk Reversibility	Technical and material compatibility: Hygrothermal risk Structural risk Corrosion risk Salt reaction risk Biological risk	Reversibility is defined as separate KPI
	Reversibility	
Heritage significance: Risk of material, constructional, structural impact Risk of architectural, aesthetic, visual impact Risk of spatial impact	Heritage value compatibility	This is defined as the primary KPI and replace the indicator "heritage significance"
	Visual impact	This replaces the parts in bold of the indicator "risk of architectural, aesthetic, visual impact "
	Spatial impact	Same as the "risk of spatial impact"
	Architectural impact	This replaces the parts in bold of the indicator "risk of architectural , aesthetic, visual impact" and it is merged under visual impact.
	Impact on authenticity	This replaces the indicator "risk of material, constructional structural impact"
	Durability	This is in addition to the indicators of the EN 16883
Economic viability	-	Evaluated in the cost thematic area
Energy	-	Evaluated in the energy thematic area
Indoor environmental quality	-	Evaluated in the IAQ thematic area
Impact on the outdoor environment	-	Evaluated in the energy thematic area

Influence on the use and the users of the building	-	Partially evaluated in the energy and IAQ thematic areas
Consequences of change of use	-	Not relevant to HeriTACE renovation scenarios
Consequences of adding new technical room	Share of construction / demolition volume Spatial impact	Two indicators are used for evaluating this aspect with respect to volume change and transformation of space
Ability of building users to manage and operate control systems	-	Evaluated in the energy and IAQ thematic areas

Heritage value compatibility

The heritage value compatibility KPI consists in the evaluation of the KPIs described in this chapter. The weighting of single KPI outcomes to form the overall heritage value compatibility of a renovation scenario will be evaluated during the development of the MADM.

Technical and material compatibility

The Technical and material compatibility KPI consists of a list of sub-indicators for the evaluation of different characteristic risks of historic buildings. The evaluation of this KPI is performed in HeriTACE by considering if for each of its sub-indicators the proposed technological renovation solution poses a risk, by producing a YES/NO result. It is worth noting that the indicators under Technical and material compatibility are case specific, meaning the type of building and renovation scenario have a large influence on the impact monitored by each of these indicators, and therefore their full assessment, which is outside the scope of HeriTACE, can be performed within the administrative procedure of renovation permit to be submitted to city councils.

Hygrothermal risk

Organic hygroscopic materials (such as wood) are sensitive to changes in RH, which affect their equilibrium moisture content (EMC), causing dimensional changes that can lead to stress, fractures, and deformation. Sharp fluctuations of RH and temperature can cause cumulative, non-recoverable damage, which may worsen with age. Determining optimal temperature and RH ranges for preservation is challenging due to the complexity and variety of materials involved. The standard EN 15757:2010 suggests a guideline for calculating recommended ranges of variation of temperature and RH of hygroscopic materials with historical values to limit climate-induced physical damage, such as risks for mould growth at interior surfaces, and risk for mould or condensation within the building fabric. RH levels in indoor environments should be stabilized within a target range based on historical climate records and short-term fluctuations and steep or frequent changes in temperature and RH should be avoided. External ambient conditions, influenced by seasons and weather extremes, should be analysed alongside internal monitoring.

The EN15757:2010 suggests the following action to obtain stable indoor RH levels:

- if the moisture content in air is constant, maintaining the temperature as constant as possible.
- if the moisture content in air is variable, vary the temperature in order to maintain a constant RH (when changes in temperature have no relevant impact).
- if the moisture content in air is variable, add or remove moisture to the air, without altering temperature (if changes in temperature have relevant impact on objects).

The fluctuations of indoor RH should be within the historical range of the indoor environment. The target range of RH levels can be defined by calculating the upper 93th percentile and the lower 7th percentile of the seasonal cycles occurring in the indoor environment. The seasonal cycles can be determined by calculating the 30-day moving average of recorded RH measurements over a 395 day period in total.

The evaluation of the Hygrothermal risk KPI in HeriTACE is performed by considering if the indoor RH and temperature conditions are favourable for leading to occurrence of hygrothermal risk in the building fabric. The outcome of the evaluation is given as a YES/NO.

Structural risk

Energy renovation of historical buildings may introduce structural challenges, particularly due to the addition of new material layers that may alter load distributions. The introduction of additional loads – whether from insulation, cladding, or mechanical systems or vertical extensions – necessitates a careful assessment of the existing load-bearing capacity. The evaluation of the Structural risk KPI in HeriTACE relies on case-specific analyses, including finite element modelling and material testing, to evaluate safety margins. The outcome of the evaluation is given as a YES/NO.

Corrosion risk

Atmospheric corrosion is a process occurring on the exposed building materials, which we find in historic buildings especially when there are unprotected surfaces in metal, stone, or brick. The corrosion rate is increased by high levels of relative humidity (80% and above) and temperature above 0 °C. The presence of pollutants and/or hygroscopic salts may further increase the corrosion risk. Therefore, the exposure to rain, sunshine, and pollutants of the building components is the large driver of corrosion risk, although a locally high corrosion rate may occur when due to poor ventilation condensation accumulates on the material surface. The estimation of the corrosion risk can be evaluated by considering the characteristics of the local environment, according to ISO 9223. These are described in Table 15.

Table 15. Corrosivity categories of indoor and outdoor environments according to ISO 9223 and ISO 12944-2:2017

Corrosivity category	Typical outdoor environment	Typical indoor environment
C1, very low	-	Heated buildings with clean atmosphere
C2, low	Rural areas	Unheated buildings where condensation can occur,
C3, medium	Urban and industrial atmospheres, coastal areas with low salinity	Production rooms with high humidity and some air pollution, e.g. food-processing plants

C4, high	Industrial areas and coastal areas with moderate salinity	Chemical plants, swimming pools
C5, very high	Industrial areas with high humidity and aggressive atmosphere and coastal areas with high salinity	Buildings or areas with almost permanent condensation and with high pollution

Since humidity is a known driver of increased corrosion risk, general considerations of the influence of climate on the likely occurrence of corrosion can be drawn based on the time a building surface is exposed to high levels of relative humidity, defined time of wetness according to ISO 12944-2:2017. Time of wetness is given for main climatic types in Table 16.

Table 16. Time of wetness of main climatic types according to ISO 12944-2:2017

Type of climate	Mean annual low temperature (0 °C)	Mean annual high temperature (0 °C)	Mean annual highest temperature (RH > 95%) (0 °C)	Time of wetness (RH > 80% and T > 0 °C) (h/year)
Extremely cold	-65	+32	+20	0-100
Cold	-50	+32	+20	150-2500
Cold temperate	-33	+34	+23	2500-4200
Warm temperate	-20	+35	+25	2500-4200
Warm dry	-20	+40	+27	10-1600
Mild warm dry	-5	+40	+27	10-1600
Extremely warm dry	+3	+55	+28	10-1600
Warm damp	+5	+40	+31	4200-6000
Warm damp, constant	+13	+35	+33	4200-6000

Corrosion risk in historic buildings in Europe has been studied in literature and a non-exhaustive list of relevant references can be found at the end of this document. Additional references to relevant ISO and EN standards:

- ISO 8044:2015, Corrosion of metals and alloys – Basic terms and definitions
- ISO 9223, Corrosion of metals and alloys – Corrosivity of atmospheres – Classification, determination and estimation
- ISO 9226, Corrosion of metals and alloys – Corrosivity of atmospheres – Determination of corrosion rate of standard specimens for the evaluation of corrosivity
- EN 12501-1, Protection of metallic materials against corrosion – Corrosion likelihood in soil – Part 1: General

The evaluation of the corrosion risk KPI in HeriTACE is performed by considering if the environmental conditions are present that may lead to corrosion decay of the building fabric and the exposure of time of the building fabric to such conditions. The outcome of the evaluation is given as a YES/NO.

Salt reaction risk

Salt efflorescence in historic buildings refers to the crystalline deposits of salts, often appearing as white or yellowish crusts, that form on brick, wood, stone and cement surfaces,

as well as in mortar joints. This phenomenon occurs due to presence of water-soluble salts in the building fabric. High indoor temperature and low RH or high airflow rates impinging on building elements may lead to evaporation of water moisture trapped inside. The migration of water moisture towards the material exposed surface and its evaporation leads salt crystals. These can lead to increased corrosion of the material. As recommended in the EN 15759-2:2018, mechanical ventilation is to be carefully considered in the case of wall dampness due to rising ground water or water percolation, since this is likely to accelerate the evaporation process and hence induce migration of soluble salts to the wall surface, salt efflorescence and masonry decay.

Causes of salt efflorescence in masonry constructions can be attributed to:

- Mortar as it is in contact with masonry elements (bricks and stones) by at least four sides. If soluble salt is present in the mortar, it will be carried into the construction element.
- Sand for use in mortar should be taken from sources free of contamination from saltwater, soil runoff, plant life and decomposed organic compounds, among others.
- Admixtures for mortar, which are classified as workability enhancers, bond enhancers, water repellents, set retarders or set accelerators, may contain soluble salts.

Salt efflorescence is experienced in wood materials when contaminated show material degradation of the middle wood cell lamella and separation of the cells wall layers. Causes of salt efflorescence can be due to the deliquescence of inorganic preservatives impregnated in the wood. Evaluation of salt efflorescence can be carried out during the condition survey of built cultural heritage, according to the guidelines given in the EN 16096:2012. The evaluation of the salt risk KPI in HeriTACE is performed by considering whether the conditions are present in the building and the technological solutions proposed in the renovation scenarios may lead to an increase of salt reaction risk. The outcome of the evaluation is given as a YES/NO.

Biological risk

Mold and decay problems in buildings are often to be attributed to moisture and water exposure of building materials. The building elements that are exposed to outdoor weather and high humidity are very likely to be prone to bio-deterioration processes. Table 17 summarizes the types of bio-deterioration processes and the attributed causes.

Table 17. Typical bio-deterioration processes of building materials and favourable conditions.

Type of organism	Typical damage process	Favourable condition range of RH or MC (%)	Favourable condition range of temperature (°C)
Bacteria	Wood, concrete, stones, metals. Corrosion, discoloration, mechanical stress, loss of tensile/compressive/shear strength	RH > 97%	-5 to +60
Mold fungi	Primarily wood. Enzymatic degradation, moisture transportation and accumulation, loss of structural integrity	RH > 75% and wood MC > 25%	0 to +50

Blue-stain fungi	Primarily wood. Change of visual appearance, increase of water permeability, increase risk of decay fungi growth	RH > 95% and wood MC > 25%	-5 to +45
Decay fungi	Primarily wood. Enzymatic degradation, rotting, and loss of structural strength	RH > 95% and wood MC > 25%	0 to +45
Algae and lichen	Wood, concrete, stones, metals. Mechanical stress, tawing, surface corrosion	Wet materials, presence of Nitrogen and low PH	0 to +45
Insects	Primarily wood. Loss of structural strength, pathway to increase of moisture accumulation and rotting.	RH > 65%	+5 to +50

The evaluation of the biological risk KPI in HeriTACE is performed by considering whether the conditions are present in the building, the extent of persistence of such conditions over time, and if the environmental conditions in the renovation scenarios may lead to an increase of biological degradation of the building fabric. The outcome of the evaluation is given as a YES/NO.

Durability

Durability in building materials refers to their ability to withstand environmental stresses and degradation over time, ensuring long-term functionality and reducing maintenance needs. Factors influencing durability include material properties, environmental conditions, construction practices, maintenance levels, and reparability. Durable materials resist weathering, chemical reactions, biological attacks, and other factors that can cause the deterioration of their performances. The use of durable materials and durable combinations of materials lead to less frequent repairs and maintenance, saving time and money in the long run, contributing to the longevity of historic buildings and their sustainability. At the same time, the choice of compatible and durable solutions may improve the preservation of such heritage buildings while avoiding that decay issues occur.

Several ISO standards address the durability of materials:

- ISO 13823:2008 (General principles on the design of structures for durability). This standard provides a framework for verifying the durability of structures by considering environmental actions (weathering), mechanical actions (loads, stresses), and material degradation, and assessment of performance failure (cracking, loss of strength). It ensures the structure's reliability throughout its design service life.
- ISO 6892-1 (Metallic materials – Tensile testing – Part 1: Method of test). This standard specifies the method for tensile testing of metallic materials,
- ISO 148-1 (Metals – Charpy impact testing). This standard is used for evaluating the toughness of metals under sudden impact forces, which is important for assessing their durability in various applications.
- ISO 6508 (Metallic materials – Rockwell hardness test) and ISO 6507 (Metallic materials – Vickers hardness test). These standards specify the methods for hardness testing, used to determine a material's resistance to indentation and deformation.

- ISO 21887:2007 (Durability of wood and wood-based products – Use classes). This standard categorizes wood and wood-based products based on their durability under different environmental conditions.
- ISO 9652-4:2000 This standard provides specific test methods for masonry materials, including masonry units, mortars, and masonry elements. These methods are used to determine the properties needed for the design of masonry structures.

In HeriTACE, the durability KPI is assessed for the building components and materials to be installed in the heritage renovation scenarios. The evaluation is based on the performance of materials and components applied to heritage buildings given by producers and past experience in other relevant applications, and it is given in years of service life of material/component between repair/major replacement steps. A first screening of materials and components is done according to their technical compatibility (as described in 3.4.2). Thereafter, of those compatible materials and components, the best performing in terms of durability are selected.

Visual impact

The visual impact KPI is evaluated in HeriTACE by considering a list of characteristic parameters of the materials/building component/design solutions in the renovation scenarios which together define the final aesthetic and visual appearance of the renovated building. The evaluation of each parameter is to be performed at different scales of the renovation scenario, from the material scale to the neighbourhood scale, as described in Table 18. Several ISO standards are suggested to aide in the evaluation process. However, the evaluation can rely on current procedures employed by city conservation offices in the evaluation of energy renovation projects of historical buildings. The evaluation output is given as a subjective five-point rating scale (low, medium-low, medium, medium-high, high).

Table 18. List of parameters contributing to the visual impact KPI

Parameter contributing to the visual impact	Scale of assessment			
	Material	Building component	Building	Neighbourhood
Color	Matching (hue, luminosity, saturation) to the original materials	Coherence (hue, luminosity, saturation) with existing/original components	-	Coherence (hue, luminosity, saturation) with the neighbourhood palette
Proportion	-	Matching (height, width, depth) to the original design between elements of the same component	Matching (height, width, depth) to the original design between different building components	Matching (height, width, depth) to the original layout of the neighbourhood (e.g. the street front)
Specularity	Matching (glossiness) to the original material	Coherence (glossiness) with existing/original components	-	Coherence (glossiness) with the

				neighbourhood palette
Texture	Matching (roughness) to the original material	-	-	-
Patina	Evaluation on the ageing of surface material to match the original	Coherence with existing/original components	-	-
Surface finish and pattern	Type of finish based on application and treatment. Matching to original applications.	-	-	-

Relevant standards for evaluation of color matching.

- ISO 105-J03:2009: This standard provides a method for calculating color differences between materials, which can be useful for assessing color matching.
- ISO 18314-4:2020: This standard focuses on metamerism, which is the phenomenon where colors match under one light source but not under another.
- ISO 11037:2011: This standard provides guidelines for sensory evaluation of the color of products, which can complement instrumental measurements.
- ISO 3668:2017: This standard specifies the visual comparison of color for paints and varnishes.

Relevant standards for the evaluation of material specularity

The primary ISO standard for evaluating the specularity (gloss) of materials is ISO 2813:1994. This standard outlines a photometric method for measuring the specular gloss of paints and varnishes, which is relevant for assessing the reflective characteristics of various surfaces. It defines the measurement of reflected light intensity at a specific angle, crucial for understanding how surfaces reflect light and appear glossy or matte. While ISO 2813 is primarily focused on coatings, its principles can be adapted for other materials as well.

Relevant standards for the evaluation of material roughness

ISO 21920 details surface roughness measurements, providing guidelines for describing and evaluating the surface texture of components. It defines basic symbols and parameters for indicating surface roughness on technical drawings and documents.

ISO 25178 defines how to specify and measure 3D surface texture focusing on areal surface texture and providing a framework for understanding and characterizing the three-dimensional features of surfaces.

Spatial impact

The spatial impact KPI consists in the assessment of the changes introduced in the renovation scenarios with respect to the followings:

- change of use of single building spaces and rooms
- addition of new spaces and rooms with new functions (e.g. technical rooms)
- change of the original navigation in the building due to new partitioning and/or new functions
- change of original use of outdoor spaces by covering and/or addition of new volumes
- addition of new elements for renovation purposes (e.g. addition of internal insulation)

The evaluation is based by considering the importance of the spaces in the overall architecture of the building (assessed during the building condition survey), and the extent of the change. The evaluation output is given as a subjective five-point rating scale (low, medium-low, medium, medium-high, high).

An objective evaluation of the spatial impact due to renovation scenarios can be performed by considering the isovist of the space. The isovist is the visual representation of the set of all points visible from a single vantage point in a given moment. This defines the spaces that can be seen by a defined location. The following metrics can be used for the spatial assessment of the renovation scenarios:

- Isovist area: defined as the area of all space visible from a vantage point in the building plan
- Isovist perimeter: defined as the length of the edges of the space visible from a vantage point in the building plan
- Isovist occlusivity: defined as the proportion of edges of the isovist perimeter that occlude areas of the building plan
- Vista length: defined as the longest single view perceivable by each vantage point.

Share of construction / demolition volume

This indicator helps understanding the impact on share of material waste due to renovation activities, hence giving the evaluator the opportunity to favour renovation scenarios that reduce this amount. HeriTACE HLO 4 specifically addresses this topic with the goal of 10% reduction of 10% waste reduction. The evaluation of this KPI is performed by comparing the share of either the construction or demolition volume between two alternative renovation scenarios.

Impact on authenticity

The preservation of original building elements is crucial to protect the heritage value and significance of the building. The renovation scenarios follow the principle of minimal intervention, thus ensuring original elements are preserved whenever possible. However, in some circumstances this is not possible due to the condition of the building element (damaged or failure of performance) and/or when it is in clear contrast with the installation of technological solutions aimed at improving the building energy performance and occupants' comfort. The evaluation assessment is therefore based on the significance and importance of the original element in the overall building's heritage and architecture value (assessed in the building condition survey). Change of use of the original function of building elements that ensure their preservation and improve the building energy efficiency and occupants' comfort are considered as enhancements. The evaluation output is given as a subjective five-point rating scale (low, medium-low, medium, medium-high, high).

Reversibility

Reversibility in architecture refers to the ability of a building to be dismantled, deconstructed, or transformed without significant damage to its components or materials, allowing for reuse, recycling, or repurposing. This concept promotes a more sustainable and resource-efficient approach to construction, minimizing waste and maximizing the lifespan of building materials. Design for Disassembly (DfD) is a design approach developed in the manufacturing industry aiming at reducing the materials, resources, and energy use in the production process. The ISO 20887:2020 defines the application of DfD in the context of architecture design as the approach that facilitates disassembly at the end of the building useful life, aiming at reusing, recycling, and energy recovering building's components and materials. In HeriTACE, reversibility is intended as the ability to turn the building to the state preceding the implementation of a renovation scenario without causing irreversible damage to the historic components, either destroying elements or parts of the historic construction. Despite being developed for the manufacturing industry and often applied in the construction industry within prefabrication projects, DfD guidelines provides useful principles for the evaluation of reversibility of renovation scenarios of historic buildings. The most relevant are listed below:

- Use mechanical connections rather than chemical bonds. Avoid using adhesives, resins and coatings.
- Minimize the number of different connections.
- Avoid joints and screws that limit reutilization
- Use joints and material fixings compatible with the connected parts
- Use joints and connectors that can withstand repeated usage.
- Facilitate the separation of layers and components. Layer theory defines that a construction should follow an assembly procedure to facilitates the replacement of layers with shorter service life without interfering with other layers. The components undergoing a higher replacement rate must be located closer to the building fabric surface, so to be reached more easily for removal without damaging or interfering with the rest of the building fabric.
- Favour the application of visible construction systems, including elements and connections

The evaluation output of the Reversibility KPI is given as a subjective five-point rating scale (low, medium-low, medium, medium-high, high).

4. Conclusion

This report presented a preliminary mapping of relevant KPIs and the definition of a KPI assessment framework for the assessment of the HeriTACE renovation scenarios within the Multi-Dimensional Assessment Model. The KPI were grouped according to four areas of impact: Energy and Environmental Impact, Cost, IEQ, and Heritage and Architecture. Methods for the calculation of each KPI were provided and additional indicators (here named as Performance Indicators, PIs), which are not part of the MDAM, were identified. Given the complexity of the framework and the variety of methods and indicators, the proposed indicators and their methods of evaluation will be revised after being tested on some of the case studies of HeriTACE by evaluating the following aspects:

- their significance at representing the performance of the renovation scenarios (e.g. to what extent they are proxy indicators in the evaluation process)
- their easiness of being understood by non-experts and the easiness of the results of the evaluation to be translated into practical and actionable solutions.
- their ability of providing linear, consistent, and non-contradictory results among the different renovation scenarios

A new and revised framework will be then produced in Deliverable D5.7. A summary of all the KPIs described in this document is given in table below.

Table 19. List of KPIs

Area of Impact: Energy and Environmental Impact		
KPI	Metric	Evaluation criteria
Primary Energy Use	kWh/m ² year	Performance renovation scenario / baseline
Energy Use	kWh/m ² year	Performance renovation scenario / baseline
Energy Delivered	kWh/m ² year	Performance renovation scenario / baseline
Heating/Cooling peak power	kWp	Performance renovation scenario / baseline
Share of renewable and residual energy source	%	Performance renovation scenario / baseline
Operational GHG emissions	kgCO ₂ eq	Performance renovation scenario / baseline
Area of Impact: Cost		
Total Cost of Ownership	EUR/m ²	Performance renovation scenario / baseline
CAPEX	EUR/m ² or EUR/building component	Performance renovation scenario / baseline
OPEX	EUR/m ² or EUR/building component	Performance renovation scenario / baseline
Cost of CO ₂ reduction	EUR/kgCO ₂ eq	Difference of TCO / difference of operational emissions
Cost of PE savings	EUR/kWh	Difference of TCO / difference of primary energy
Payback Period	years	Difference of CAPEX / difference of OPEX
Area of Impact: IEQ		

Thermal comfort	°C/hour CATII	Performance renovation scenario / baseline, weighted
IAQ	ppm/hour CATII	Performance renovation scenario / baseline, weighted
Overheating	°C/hour CATII	Performance renovation scenario / baseline, weighted
Relative Humidity	%	Performance renovation scenario / baseline
Area of Impact: Heritage and Architecture		
Heritage value compatibility	-	Performance renovation scenario / baseline
Technical and material compatibility	-	YES/NO
Durability	years	-
Visual Impact	-	Five-points rating scale
Spatial Impact	-	Five-points rating scale
Share of construction / demolition volume	%	-
Impact on authenticity	-	Five-points rating scale
Reversibility	-	Five-points rating scale

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