HVAC-concepts for Heritage Buildings

Deliverable D3.1

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Executive Summary

The renovation and rehabilitation of historic buildings demand a careful approach to balance cultural preservation with modern requirements like energy efficiency, structural integrity, and occupant comfort. This process involves tailored assessments to ensure interventions prioritize conservation and avoid altering the building's defining attributes.

This report identifies and categorizes HVAC components into generation, emission, and ventilation systems, focusing on their suitability for heritage building interventions, based on a review of existing systems in literature and in the market. Within this longlist of HVAC solutions, each component is detailed in data sheets, highlighting technical specifications, aesthetic considerations, sustainability, integration, reversibility, and cost. Pros and cons are included to aid in selecting the most appropriate solutions, ensuring ease of maintenance and potential for future upgrades. Additionally, evaluation criteria and rating definitions are provided to support informed decision-making for these sensitive interventions.

Finally the study proposes a shortlist of tailored HVAC concepts for the various building archetypes studied in the HeriTACE project (as defined in D5.1), considering the specific requirements of different climate zones. For each climate zone, the HVAC solutions address regional thermal demands, seasonal variations, and environmental conditions to ensure energy efficiency and occupant comfort.

For each building archetype, multiple scenarios are explored, presenting a range of HVAC strategies, including new installations, upgrades, and hybrid systems. These scenarios are designed to accommodate unique building constraints, such as heritage preservation, space limitations, and existing infrastructure, while optimizing performance.

This deliverable should be considered in combination with building envelope (D2.2) and R_2ES (D4.2) concepts to achieve a holistic overview of the retrofit solutions and scenarios for the heritage building archetypes targeted in HeriTACE. The concepts will be applied to the building and neighbourhood energy modelling to assess their performance (T3.2, T3.5 and T4.5).

Introduction

The renovation and rehabilitation of a historic building should consider several aspects, such as cultural and historic value, conservation conditions, building constraints, etc.

Usually, such kind of intervention requires a tailored assessment that balances the different needs of the building, including structural integrity, energy efficiency, occupant comfort, etc., prioritizing the conservation aspects in order that the intervention does not cause a loss or alteration of the attributes that characterize such kinds of buildings.

In such respect, when installing or upgrading an HVAC system in heritage buildings, several factors should be considered to meet the needs of the building's occupants while preserving its authenticity.

Each heritage building presents unique challenges and requirements. In some cases, it may be necessary to install a new HVAC system due to obsolete equipment. In other instances, existing heating and cooling systems, which may hold historical significance, can be updated to meet modern standards and comfort levels.

In any case, new HVAC systems should involve minimal intervention to avoid damaging the building's structural and aesthetic elements. This approach aligns with the Venice Charter for Conservation and Restoration, which emphasizes compatibility, minimum intervention, reversibility, distinguishability, expressive authenticity, durability, and respect for the original fabric.

In general, water-based plumbing systems, such as hydronic radiators, fan coils, and radiant tubes, are often smaller and less intrusive than forced-air HVAC ducts, making them suitable for heritage buildings. Centralized air conditioning systems offer high climate control efficiency, with condensers typically located outside to minimize the building's footprint. In some cases, combined systems using water for heating and cooling and ducts for ventilation may be necessary to address specific building requirements. In some cases, combined systems using water for heating and cooling and ducts for ventilation may be necessary to address specific building requirements.

Special attention must be given to the maintenance, repair, and potential future upgrades of these systems. They should be designed for ease of implementation to avoid excessive costs and difficulties throughout their lifespan.

The integration of ventilation systems, heat distribution, and heat generators in heritage buildings should be deeply analysed, case by case, to ensure they meet modern needs without compromising the building's integrity.

In this report a longlist of solutions and different shortlists are composed. The longlist consists of a series of components and concepts, which have been classified into generation (if it is coupled with emission unit), emission, ventilation and control systems that could potentially be used in the rehabilitation of heritage buildings, will be illustrated. These components have been selected both from existing ones on the market and from those that are not on the market but for which studies have been done in publications, reports, etc.

They serve as examples of systems that have characteristics particularly suitable for intervention in heritage buildings.

In this regard, in order to present the main information about each product, including technical aspects, aesthetic aspects, integration with the building, reversibility, sustainability, and product cost, data sheets have been prepared for each one. Additionally, each sheet highlights the pros and cons of the components, to underline the best application for each product.

For completeness, a definition of each information/parameter described in the data sheets is provided below, moreover, for some of them are also provided a description of the evaluation rating adopted.

List of information	Description
General information	
Product name	Name to identify a specific component in the market
Brand name	Name to identify a company or product
Source website	Source URL where information or content on the product is published
Description	A brief description of the product
Image/scheme	Generic images of the product
Technical and operational parameters	
Integration type	Type of system, such as generation, emission or ventilation
Heating/ Cooling system type	Type of technology adopted into the system to provide heating, cooling or ventilation
Dimensions (mm)	Length, Width and Height of the product expressed in mm
Weight (kg)	Weight of the product expressed in kg
Max thermal power (kW)	Maximum thermal power produced by the product in kW
Efficiency (%)	Efficiency of the product expressed in %
Efficiency class	The energy class of the product according to the energy label
COP	Coefficient of Performant of the product
EER	Energy Efficiency Ratio of the product
Acoustic rating (dB)	The sound intensity of the product expressed in dB
Control system	
Control type	Type of control technology installed into the product
Sensor type	Type of monitoring sensors integrated into the product
Communication protocol	Type of communication protocol adopted into the system
Architectural values	
Integration impact	Describe the impact of incorporating the product or system on the building's structure
Visibility	Describe the level of visibility of the product after the installation
Reversibility	Describe the ability to undo or remove a change or installation of a product without causing permanent damage or alteration to the original state

Conservation compatibility	Describe how well a product or system aligns with preserving the historical or cultural integrity of the building
Commercialisation	
Technology Readiness Level	Classified according to the following list: TRL 1 basic principles observed TRL 2 technology concept formulated TRL 3 experimental proof of concept TRL 4 technology validated in lab TRL 5 technology validated in relevant environment (industrially relevant environment in the case of key enabling technologies) TRL 6 technology demonstrated in relevant environment (industrially relevant environment in the case of key enabling technologies) TRL 7 system prototype demonstration in operational environment TRL 8 system is complete and qualified TRL 9 actual system proven in operational environment (competitive manufacturing in the case of key enabling technologies; or in space) n.a. not applicable
Investment cost	Investment cost rating of the product based on a scale that ranges from the cheapest "€" to the most expensive "€€€". It is evaluated by comparing the different products analysed
Operational cost	Operational cost rating of the product based on a scale that ranges from the cheapest "€" to the most expensive "€€€". It is evaluated by comparing the different products analysed
Sustainability	
GHG emission (operational)	Greenhouse gas emissions due to the operational phase. It is classified according to a rating ranging from the lowest value "+" to the highest one "+++". It is evaluated by comparing the different products analysed
GHG emission (embedded)	Embedded greenhouse gas emissions over the entire lifecycle of the product. It is classified according to a rating ranging from the lowest value "-" to the highest one "---". It is evaluated by comparing the different products analysed
Pros and cons	
Pros	List of pros of the product
Cons	List of cons of the product

Finally, for each archetype, tailored HVAC concepts have been proposed and thoroughly analysed, considering the specific requirements of different climate zones and the unique characteristics of each archetype. The analysis includes distinct scenarios for HVAC systems, highlighting the best-suited approaches based on climatic conditions, building features, and energy performance goals.

For each climate zone, the study examines the regional thermal demands, seasonal variations, and environmental factors, providing customized solutions to optimize heating, cooling, and ventilation efficiency. The HVAC concepts are aligned with the climatic challenges of each zone, ensuring they deliver both occupant comfort and energy efficiency.

For each archetype, multiple scenarios have been explored, showcasing various HVAC strategies that balance the architectural and operational needs of the buildings. The scenarios include options for new installations, system upgrades, and hybrid approaches, offering flexibility to address building constraints such as heritage preservation, space limitations, or existing infrastructure.

This comprehensive approach ensures that the proposed HVAC systems are not only technically and environmentally sound but also adaptable to the diverse conditions and constraints of the archetypes and climate zones. The discussion highlights the strengths and limitations of each solution, offering a clear roadmap for implementation tailored to specific regional and building contexts.

LONGLIST of HVAC solutions

1. HEAT GENERATION

1.1. HEATING & COOLING

1.1.1. Heat pumps

General information

☒	☒	☐

Product type	Heat pumps
Brand name	Stone M1 - Innova
Source website	https://www.innovaenergie.com
Description	It is a monobloc water-air heat pump that includes the cooling circuit, circulator, safety valve, and expansion vessel, which is why the connection is made through hydraulic lines.
Image/scheme	

Technical and operational parameters

Integration type	Generation
Heating/ Cooling system type	Hydronic heating and cooling
Dimensions (mm)	Variable
Weight (kg)	Variable
Max thermal power (kW)	15
Efficiency (%)	n.a.
Efficiency class	A+++
COP	Variable 4,74 -4,70
EER	Variable 4,33 – 4,32
Acoustic rating (dB)	54 - 60

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Control system

Control type	n.a.
Sensor type	n.a.
Communication protocol	n.a.

Architectural values

Integration impact	Low: It is an outdoor components adjacent to the building and has a compact design.
Visibility	Medium: While it is located outside, it can be concealed with structures or vegetation, and its design is appealing.
Reversibility	Good: It offers easy removability
Conservation compatibility	Although the aesthetic does not align with the historic context, it can utilize the existing piping to prevent damages.

Commercialisation

Technology Readiness Level	TRL 9
Investment cost	€€€
Operational cost	€

Sustainability

GHG emission (operational)	+
GHG emission (embedded)	- - -

Pros and cons

Pros	Demand-controlled, featuring a backup system for the heat pump that utilizes outdoor air. It is user-friendly for the end user. The installation process is fast and simple. It helps conserve energy.
Cons	It does not operate at high temperatures.

1.1.2. Hybrid Pellet heater - Heat pump

General information

☒	☒	☐

Product type	Hybrid Pellet heater - Heat pump
Brand name	GreenFOX - Oekofen
Source website	https://www.oekofen.com
Description	The basic system consists of a classic water-to-air heat pump, which can operate independently. It has the special feature of being combined with a pellet heating system, thus providing a hybrid solution with greater independence and diversification of the energy source. It is suitable for both new constructions and the replacement of heating systems. The flow temperature reaches 65°C.
Image/scheme	 

Technical and operational parameters

Integration type	Generation
Heating/ Cooling system type	Hydronic heating and cooling
Dimensions (cm)	1068 x 1430 x 700
Weight (kg)	210
Max thermal power (kW)	14
Efficiency (%)	n.a.
Efficiency class	A++++/A++
COP	5,4

EER	4,5
Acoustic rating (dB)	54,3

Control system

Control type	n.a.
Sensor type	n.a.
Communication protocol	n.a.

Architectural values

Integration impact	Medium: existing distribution and emission could be preserved. Two large generation units should be integrated, which can cause difficulties.
Visibility	Low: technical installations can be integrated in basement (or attic)
Reversibility	High: generation systems can easily be replaced by other.
Conservation compatibility	Particularly suitable for monuments with high heritage values. No retrofit solutions ask for high temperatures when cold outside temperatures. Most of the time, the heat pump will be sufficient, when needed the pallet boiler can produce heat.

Commercialisation

Technology Readiness Level	TRL 9
Investment cost	€€€
Operational cost	€

Sustainability

GHG emission (operational)	++
GHG emission (embedded)	- - -

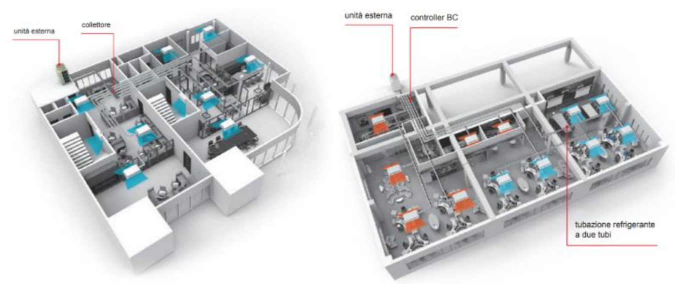
Pros and cons

Pros	Use a heat pump when possible, pellets when needed, while preserving existing emissions. This approach offers more flexibility to achieve greater efficiency with more sustainable consumption.
Cons	Pellets are carbon neutral but not carbon-free, and there is a risk of pollution.

1.1.3. VRF System

General information

☒	☒	☐

Component	VRF System
Brand name	VRF MITSUBISHI
Source website	https://climatizzazione.mitsubishielectric.it
Component or whole system	Whole system
Description	The VRF system is a direct expansion air conditioning system with variable refrigerant flow that transports heating or cooling energy from the outdoor unit to the terminal units in various indoor rooms of the building through a refrigerant fluid. Research is being done that allows VRF systems to use CO_2 as refrigerant, which has a lot lower GWP. The lamination valve is placed in both the outdoor unit and the indoor units; this allows for larger distances to be covered and greater power to be handled than in the previous system. VRF systems can have an intermediate component, a recuperator, which enables heat recovery. This feature allows the system to operate its indoor units at different speeds, heating and cooling simultaneously. The connection consists of three pipes: liquid, low-pressure gas, and high-pressure gas.
Image/scheme	

Technical and operational parameters

Integration type	Emission, distribution and generation
Heating/ Cooling system type	Air heating and cooling
Dimensions (cm)	Variable
Weight (kg)	Variable
Max thermal power (kW)	Variable
Efficiency (%)	Variable
Efficiency class	Variable
COP	Variable

EER	Variable
Acoustic rating (dB)	Variable

Control system

Control type	Local or remote control
Sensor type	Temperature
Communication protocol	Wi-Fi

Architectural values

Integration impact	Medium: VRF components should be integrated in furniture and ceiling to make the impact not too big. Outdoor unit is needed, which will have an impact as well.
Visibility	Medium: when build-in the visibility will be limited. Outdoor unit will be visible.
Reversibility	Low: whole system with piping, from outdoor the indoor units, different units in different rooms.
Conservation compatibility	Room temperatures can be adjusted individually, which is suited for heritage townhouses.

Commercialisation

Technology Readiness Level	TRL 9
Investment cost	€€€
Operational cost	€€

Sustainability

GHG emission (operational)	++
GHG emission (embedded)	- - -

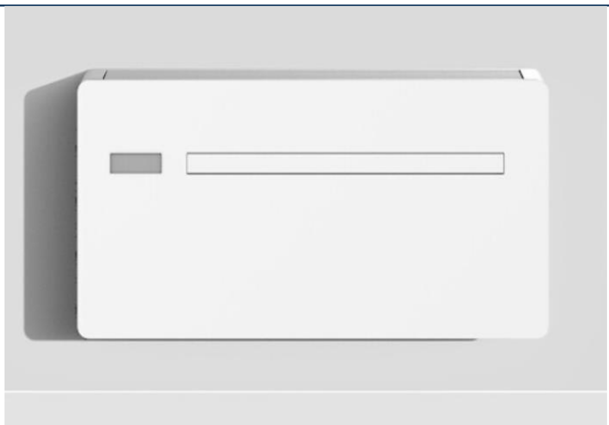
Pros and cons

Pros	Cooling and heating can be regulated per room and heat from one room can be recuperated to heat up other.
Cons	Large outdoor unit and potentially harmful cooling liquid.

1.1.4. Air conditioning with heat pump without external unit

General information

☒	☒	☐

Product type	Air conditioning with heat pump without external unit
Brand name	2.0 - Innovaenergie Srl
Source website	https://www.innovaenergie.com
Description	It is similar to a traditional air conditioner but without the external unit, so with one compact unit, you get cooling, heating, ventilation, and dehumidification. To function, it requires heat exchange, which occurs through two holes with a diameter of 162 mm, directly connecting to the outside. It fits perfectly into existing domestic environments, especially in historical settings where it is challenging to install the usual external unit.
Image/scheme	

Technical and operational parameters

Integration type	Emission without generation unit outside
Heating/ Cooling system type	Air heating and cooling
Dimensions (mm)	1010 × 165 × 549
Weight (kg)	50
Max thermal power (kW)	2.66-2.80
Efficiency (%)	81
Efficiency class	A-A+
COP	4.31
EER	4.32
Acoustic rating (dB)	27-41

Control system

Control type	n.a.
Sensor type	n.a.
Communication protocol	n.a.

Architectural values

Integration impact	High: modern aesthetic, therefore difficult to integrate
Visibility	High indoor, minimal outdoor (two holes)
Reversibility	Medium: it requires two holes in the masonry, leaving traces in case of uninstallation
Conservation compatibility	The aesthetic is not compatible with historic context; however, it could exploit the existing plumbing system

Commercialisation

Technology Readiness Level	TRL 9
Investment cost	€
Operational cost	€€€

Sustainability

GHG emission (operational)	+
GHG emission (embedded)	+

Pros and cons

Pros	No outdoor unit. One compact indoor unit with an attractive design. Routine maintenance is uncomplicated.
Cons	It must be installed on an external perimeter wall with two large openings in the external wall per unit. It does not perform well in large rooms over 50 sqm.

1.1.5. Split air conditioning

General information

☒	☒	☐

Product type	Split air conditioning
Brand name	ARTCOOL Gallery - LG
Source website	https://www.lg.com/
Description	It is a split air conditioner with a heat pump that has the functions of cooling, heating, and dehumidification. This model features a special design; in fact, it has an LCD screen that can be used for its customizable appearance.
Image/scheme	

Technical and operational parameters

Integration type	Emission and generation
Heating/ Cooling system type	Direct expansion system
Dimensions (mm)	600×600×146 (indoor unit) 770x545x288 (external unit)
Weight (kg)	14.4 (indoor unit) 34.4 (external unit)
Max thermal power (kW)	4
Efficiency (%)	n.a.
Efficiency class	A++/A+
COP	4.15
EER	5.13
Acoustic rating (dB)	60

Control system

Control type	Local or remote control
Sensor type	Temperature
Communication protocol	Wi-Fi

Architectural values

Integration impact	Medium: the system can be applied on the walls of the rooms as standard conditioner system but it needs the preparation of refrigeration piping.
Visibility	Medium: the emission system has a low level of visibility compared to traditional systems. However, as in standard systems the conduits are visible unless they are built into the walls
Reversibility	Yes
Conservation compatibility	Very low impact on the building

Commercialisation

Technology Readiness Level	TRL 8
Investment cost	€€
Operational cost	€€

Sustainability

GHG emission (operational)	+++
GHG emission (embedded)	++

Pros and cons

Pros	Ease of installation. Ease of handling
Cons	Cannot be used for large spaces.

1.2. HEATING and/or COOLING & VENTILATION

1.2.1. Exhaust air heat pump

General information

☒	☐	☒

Product type	Exhaust air heat pump
Brand name	Endura Systeem E+ Renson
Source website	https://dam.renson.eu
Description	This product integrates controlled mechanical ventilation with an air/water heat pump in a single unit in an intelligent and high-performance manner. It has the capability to supply quality fresh air to the indoor environment, generate heat for heating, and produce domestic hot water. Additionally, it can be combined with other technologies, allowing for hybrid use. It is well suited for both new buildings and renovations.
Image/scheme	

Technical and operational parameters

Integration type	Generation
Heating/ Cooling system type	Hydronic heating, cooling and ventilation
Dimensions (mm)	640
Weight (kg)	146
Max thermal power (kW)	3.5
Efficiency (%)	n.a.

Efficiency class	A+
COP	3,94
EER	-
Acoustic rating (dB)	49 dB

System type	Exhaust
System configuration	Centralized
Flow type	Variable
Heat recovery	Yes
Humidity recovery	No
Dimensions (mm)	640
Weight (kg)	146
Design flow rate (m^3/s)	0.11
Energy performance	n.a.
Acoustic performance (dB)	49

Control system

Control type	n.a.
Sensor type	n.a.
Communication protocol	n.a.

Architectural values

Integration impact	Medium: unit itself is quite compact. Exhaust ventilation system, so only ducts for the exhaust air are needed. Natural supply openings are needed with potentially high impact.
Visibility	Medium: unit can be in basement/attic. Ducts can be visible
Reversibility	High: unit can easily be removed.
Conservation compatibility	Combines ventilation and heat production in one unit/system. Efficient way of heating water.

Commercialisation

Technology Readiness Level	TRL 9
Investment cost	€€€
Operational cost	€

Sustainability

GHG emission (operational)	+
GHG emission (embedded)	- - -

Pros and cons

Pros	Compact size with no need for external units. High energy recovery from the air is achieved.
Cons	It is not possible to produce chilled water or air for air conditioning.

1.2.2. Air/air heat pump with balanced ventilation

General information

☒	☒	☒

Product type	Air/air heat pump with balanced ventilation / Exhaust air heat pump
Brand name	ComfoClime - Zehnder
Source website	https://www.zehnder.be
Description	This unit integrates a balanced heat-recovery ventilation system with a ducted air-to-air heat pump to condition the supply air. This setup enables the ventilation system to provide both heating and cooling to the building. It facilitates temperature control and dehumidification of the supply air. Additionally, it combines high passive energy recovery with the active contribution of the heat pump.
Image/scheme	 

Technical and operational parameters

Integration type	Emission and generation
Heating/ Cooling system type	Air heating, cooling and ventilation
Dimensions (cm)	580 x 720 x 840
Weight (kg)	62
Max thermal power (kW)	2,4 kW at 600 m^3/h
Efficiency (%)	n.a.
Efficiency class	n.a.
COP	1,89-3,29
EER	2,68-3,59
Acoustic rating (dB)	58

System type	Balanced
System configuration	Centralized

Flow type	Constant
Heat recovery	Yes
Humidity recovery	n.a.
Dimensions (cm)	580 x 720 x 840
Weight (kg)	62
Design flow rate (m^3/s)	600 m^3/h
Energy performance	n.a.
Acoustic performance (dB)	58 dB

Control system

Control type	n.a.
Sensor type	n.a.
Communication protocol	n.a.

Architectural values

Integration impact	High: Unit itself is compact and can be placed in technical room. Ducts needed for heat pump and ventilation have a very high impact on the building
Visibility	Medium: Ducts can be very visible; unit will be visible as well
Reversibility	Medium: unit can be removed easily; ducting is more difficult
Conservation compatibility	Heating and ventilation are combined in one system, making a separate distribution system for the hydronic system unnecessary.

Commercialisation

Technology Readiness Level	TRL 9
Investment cost	€€€
Operational cost	€

Sustainability

GHG emission (operational)	+
GHG emission (embedded)	- - -

Pros and cons

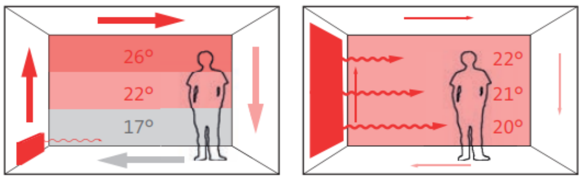
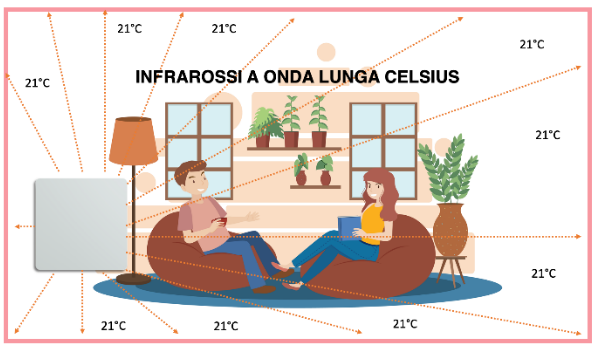
Pros	Heat pumps can be very efficient due to heat recuperation with very low energy consumption.
Cons	A high ventilation rate is necessary to adequately heat or cool the building (beyond what is needed for hygiene), requiring extensive ducting.

2. DISTRIBUTION SYSTEMS

2.1. HEATING

2.1.1. Long-wave infrared heating

General information

☒	☐	☐
Product type	Long-wave infrared heating	
Brand name	Celsius – Tesi Group	
Source website	https://www.celsiuspanel.it/	
Description	An infrared system uses electrical energy to spread heat not only through air movement but also by radiating electromagnetic waves that interact with the bodies and surfaces they contact. If designed well, this type of operation ensures a more even distribution of heat compared to traditional heating methods.	
Image/scheme	 Convection heating (e.g. fan heater) Radiant heating (e.g. wall or infrared heating) 	

Technical and operational parameters

Integration type	Emission and generation
Heating/ Cooling system type	Electric heating
Dimensions (cm)	Variable
Weight (kg)	Variable
Max thermal power (kW)	Variable
Efficiency (%)	100
Efficiency class	-
COP	-
EER	-

Acoustic rating (dB)	0

Control system

Control type	Local control
Sensor type	Temperature
Communication protocol	n.a.

Architectural values

Integration impact	Very low: Only an electric plug is needed.
Visibility	Low: panels are visible, but can be integrated esthetical
Reversibility	Good: panels can me dismounted and leave no trace
Conservation compatibility	This can be very helpful as an addition to the existing heating systems because this is an easy installation with minimal impact on the building.

Commercialisation

Technology Readiness Level	TRL 9
Investment cost	€
Operational cost	€€€

Sustainability

GHG emission (operational)	+++
GHG emission (embedded)	+

Pros and cons

Pros	The radiative heat is perceived as more comfortable and is distributed more evenly throughout the room. The comfort feeling is reached quicker. Risk of local discomfort at cold wall and warm panel.
Cons	Heating system that is ideal for temporary heated rooms and/or in combination with another base heating system (hydronic). big difference between hot panel and cold wall can cause local discomfort.

2.1.2. Water underfloor heating between joists

General information

☒	☐	☐

Product type	Water underfloor heating between joists
Brand name	The Underfloor Heating Company
Source website	https://www.theunderfloorheatingcompany.co.uk
Description	Instead of installing the floor heating on the existing wooden floor, the space between the wooden beams is utilized. Insulation and a flat plate are installed (using brackets or small wooden supports) between the beams, upon which the heating pipes are laid. The finishing layer can be placed back on the beams without losing construction height.
Image/scheme	 Aluminium spreader plates  Aluminium insulation boards  Dry screed mix

Technical and operational parameters

Integration type	Distribution, emission

Heating/ Cooling system type	Hydronic heating and cooling
Dimensions (mm)	Height 70
Weight (kg)	25kg/mq
Max thermal power (kW)	-
Efficiency (%)	-
Efficiency class	-
COP	-
EER	-
Acoustic rating (dB)	-

Control system

Control type	n.a.
Sensor type	n.a.
Communication protocol	n.a.

Architectural values

Integration impact	Low: The original construction height is preserved because the system is installed between the wooden support beams.
Visibility	Low: there is nothing visible of the heating system
Reversibility	High: When a dry system is used, the system as a whole can be removed easily.
Conservation compatibility	When wooden floors are present, this underfloor heating system can be installed to make sure the original construction height is preserved. The finishing layer must be removed for installing, this can cause damage to the floor.

Commercialisation

Technology Readiness Level	TRL 9
Investment cost	€€
Operational cost	€

Sustainability

GHG emission (operational)	+
GHG emission (embedded)	n.a.

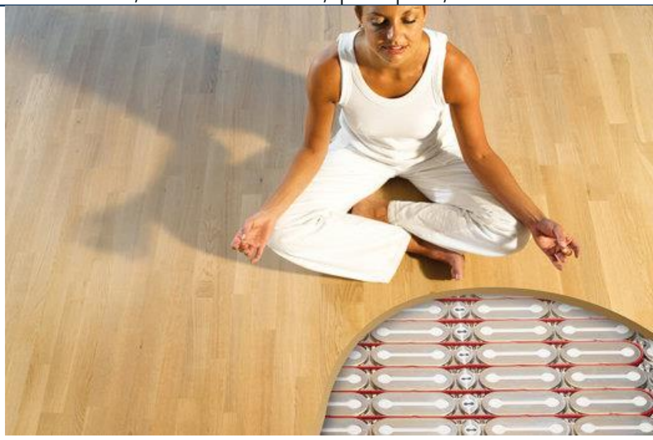
Pros and cons

Pros	No impact on construction height and quick-responding system.
Cons	A limited amount of thermal mass is activated (exception when a thin screed is used) The efficiency of the system will depend on the insulating resistance of the material covering your beams (chipboard, floorboards) and the floor finish (carpet, wood, etc.).

2.1.3. Electric underfloor heating

General information

☒	☐	☐

Product type	Electric Underfloor Heating
Brand name	Danfoss
Source website	https://www.danfoss.com
Description	This system is an electric underfloor heating solution. It has a quick response time and is easy to control. It is adaptable to all types of floor coverings, including ceramic tiles, natural stone, parquet, and more.
Image/scheme	

Technical and operational parameters

Integration type	Emission
Heating/ Cooling system type	Electric heating
Dimensions (cm)	Variable
Weight (kg)	Variable
Max thermal power (kW)	Variable
Efficiency (%)	-
Efficiency class	-
COP	-
EER	-
Acoustic rating (dB)	-

Control system

Control type	Thermostat
Sensor type	Temperature
Communication protocol	n.a.

Architectural values

Integration impact	Low: placed under the floor.

Visibility	Low: not visible
Reversibility	Low: construction work must be carried out for removal
Conservation compatibility	Can serve as additional heating to make the room comfortable without adding any intrusive systems.

Commercialisation

Technology Readiness Level	TRL 9
Investment cost	€
Operational cost	€€€

Sustainability

GHG emission (operational)	+++
GHG emission (embedded)	- -

Pros and cons

Pros	Quick-responding system.
Cons	Variation on electric resistance heating, which is not efficient and not thermally activated.

2.1.4. Radiant baseboard system

General information

☒	☐	☐

Product type	Radiant baseboard system
Brand name	Thermodul - HEKOS
Source website	https://rbm.eu/en/futura
Description	This baseboard radiant system runs on water or electricity. The heat generator can be a boiler, heat pump, or photovoltaic system. The heat is distributed evenly along the perimeter walls, which then release it into the room by radiation.
Image/scheme	

Technical and operational parameters

Integration type	Distribution, emission
Heating/ Cooling system type	Hydronic & electric heating
Dimensions (mm)	Thickness 29 mm – Height 137 mm
Weight (kg)	Variable
Max thermal power (kW)	-
Efficiency (%)	-
Efficiency class	-
COP	-
EER	-
Acoustic rating (dB)	-

Control system

Control type	Thermostatic
Sensor type	Temperature
Communication protocol	n.a.

Architectural values

Integration impact	Medium: It requires no invasive masonry work and can be integrated with existing installations.
Visibility	Low: there is nothing visible of the heating system

Reversibility	Low: can be easily removed.
Conservation compatibility	The impact is minimal therefore there is very efficient conservation..

Commercialisation

Technology Readiness Level	TRL 9
Investment cost	€€€
Operational cost	€

Sustainability

GHG emission (operational)	+
GHG emission (embedded)	- - -

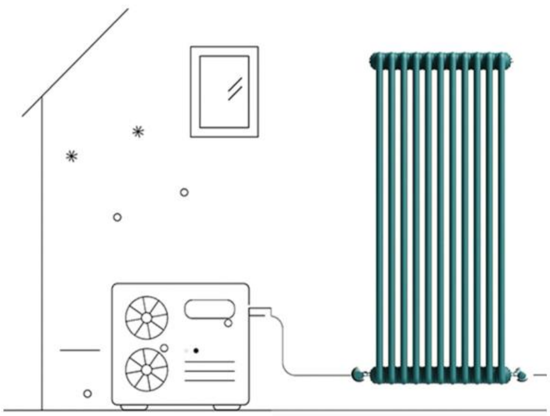
Pros and cons

Pros	Uniform heating of rooms by radiant system. Very low thickness. Speed and ease of installation
Cons	High investment costs. Furniture should not be placed too close to the walls. It can be difficult to heat very large rooms.

2.1.5. Hydronic radiators wall heating

General information

☒	☐	☐

Product type	Hydronic radiators wall heating
Brand name	Tesi - Irsap
Source website	https://www.irsap.com/it
Description	It is similar to a classic radiator, with the notable difference of being made of tubular steel, making it perfectly adaptable to new technologies such as low-temperature heat pumps. It can be fitted to existing systems by customizing the hydraulic connections, and regardless of its size, Tesi always maintains high performance.
Image/scheme	

Technical and operational parameters

Integration type	Distribution, emission
Heating/ Cooling system type	Hydronic heating
Dimensions (cm)	Variable
Weight (kg)	Variable
Max thermal power (kW)	-
Efficiency (%)	-
Efficiency class	-
COP	-
EER	-
Acoustic rating (dB)	-

Control system

Control type	-
Sensor type	Temperature
Communication protocol	Wi-Fi

Architectural values

Integration impact	Low: adaptable to the existing system and being flexible in size, no further work has to be done.
Visibility	Medium: visible and for large rooms can be cumbersome but have a pleasant design.
Reversibility	Low: There is no need to do any work on the existing system, so radiators can be removed by simply replacing them.
Conservation compatibility	It is optimally achieved because almost all residential buildings have radiators, therefore, no heavy modification is required.

Commercialisation

Technology Readiness Level	TRL 9
Investment cost	€€
Operational cost	€

Sustainability

GHG emission (operational)	+
GHG emission (embedded)	n.a.

Pros and cons

Pros	Few plant modifications, therefore low cost and installation time. Attractive design.
Cons	Cannot be used for cooling. Bulky for large rooms.

2.1.6. Radiator

General information

☒	☐	☐

Product type	Radiator
Brand name	Plan XV - Hudevad
Source website	https://hudevad.com/en
Description	It is a traditional water radiator designed to heat a room. It is especially effective for large halls or areas that are difficult to heat.
Image/scheme	

Technical and operational parameters

Integration type	Emission
Heating/ Cooling system type	Hydronic heating
Dimensions (cm)	Variable
Weight (kg)	Variable
Max thermal power (kW)	Variable
Efficiency (%)	-
Efficiency class	-
COP	-
EER	-
Acoustic rating (dB)	-

Control system

Control type	n.a.
Sensor type	n.a.
Communication protocol	n.a.

Architectural values

Integration impact	Medium: according to the spaces, the building state of the art and previous renovations, this can be more or less integrated.

Visibility	High: no way to hide, only colour can blend.
Reversibility	Low: holes need to be done in masonry for holding the system and for the water input and output. It also may leave traces after removal.
Conservation compatibility	"No conservation of Heritage value: - Aesthetics impact: difficult to hide, modern component with no blending possibilities, just with colours. - Structural impact: holes need to be done in wall for holding the system and for the water input and output."

Commercialisation

Technology Readiness Level	TRL 9
Investment cost	€€€
Operational cost	€€

Sustainability

GHG emission (operational)	0
GHG emission (embedded)	-

Pros and cons

Pros	Ideal for large rooms undergoing renovation.
Cons	Considerable visual impact.

2.2. HEATING & COOLING

2.2.1. Hydronic fan coil wall heating and cooling

General information

☒	☒	☐

Product type	Fan coil
Brand name	Relax Hybrid - Irsap
Source website	https://www.irsap.com/it
Description	It is a ventilated radiator with a steel structure, featuring a compact design and pleasing aesthetics. Its main functions include convective and radiant heating, cooling, and air conditioning. In addition to the usual hydraulic connections found in standard radiators, it requires a power supply point and optionally a condensate drain. It is adaptable to both new heat pumps and traditional heat generators.
Image/scheme	 

Technical and operational parameters

Integration type	Distribution, emission
Heating/ Cooling system type	Hydronic heating and cooling
Dimensions (cm)	Variable
Weight (kg)	Variable
Max thermal power (kW)	-
Efficiency (%)	-
Efficiency class	-
COP	-
EER	-
Acoustic rating (dB)	-

Control system

Control type	-

Sensor type	Temperature
Communication protocol	Wi-Fi

Architectural values

Integration impact	Medium: adaptable to the existing system and being flexible in size, it is necessary to create an electrical connection and condensate drain.
Visibility	Medium: visible and for large rooms can be cumbersome but have a pleasant design.
Reversibility	Low: radiators can be removed by simply replacing them.
Conservation compatibility	It is optimally achieved because almost all residential buildings have radiators.

Commercialisation

Technology Readiness Level	TRL 9
Investment cost	€€
Operational cost	€

Sustainability

GHG emission (operational)	+
GHG emission (embedded)	n.a.

Pros and cons

Pros	Can be used for cooling and heating. Attractive design.
Cons	Work must be carried out on each individual radiator.

2.2.2. Water loop Hydronic radiators wall heating and cooling

General information

☒	☒	☐

Product type	Hydronic radiators wall heating and cooling
Brand name	WLHP terminals- INNOVA
Source website	https://www.innovaenergie.com
Description	It is a water radiator that is perfectly suited to replace old radiators. It can also be described as a fan coil because it operates with water and air in a compact and efficient manner. The system circulates water throughout the year at a stable temperature of 20-30 °C, preventing condensation from forming on uninsulated pipes during the summer. The WLHP adjusts the water temperature to the ideal level, allowing each room to be efficiently heated or cooled.
Image/scheme	

Technical and operational parameters

Integration type	Distribution, emission
Heating/ Cooling system type	Hydronic heating and cooling
Dimensions (cm)	Variable
Weight (kg)	Variable
Max thermal power (kW)	3.6
Efficiency (%)	n.a.
Efficiency class	n.a.
COP	5.9
EER	4.8
Acoustic rating (dB)	52

Control system

Control type	On-board control
Sensor type	Temperature
Communication protocol	Wi-Fi

Architectural values

Integration impact	Low: adaptable to the existing system and being flexible in size.
Visibility	Low: The size is comparable to the older radiators.
Reversibility	High: radiators can be removed by simply replacing them.
Conservation compatibility	It is optimally achieved because almost all residential buildings have radiators.

Commercialisation

Technology Readiness Level	TRL 9
Investment cost	€€
Operational cost	€

Sustainability

GHG emission (operational)	+
GHG emission (embedded)	n.a.

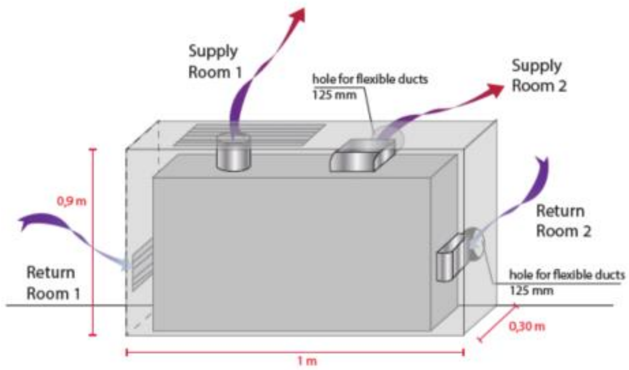
Pros and cons

Pros	Fully autonomous operation for each room. Capability to provide simultaneous heating and cooling in various spaces. Heating, summer cooling, and dehumidification all in a single device.
Cons	A modern design could conflict with historic buildings.

2.2.3. Water loop Hydronic radiators wall heating and cooling (research)

General information

☒	☒	☐

Product type	Hydronic radiators wall heating and cooling
Brand name	STILLE – HEART project
Source website	https://heartproject.eu/ https://www.stillegroup.eu/
Description	A fan coil unit which integrates a small-size DC compressor to increase the thermal power coming from the centralized DC heat pump, according to the energy demand of each room. It works both in heating and cooling mode. The unit comprises a hermetically sealed refrigeration circuit with refrigerant-to-air and refrigerant-to-water heat exchangers. The refrigeration circuit is reversed automatically by the user's thermostat. Therefore, each heat exchanger acts either as an evaporator or condenser. The airside heat exchanger adds or removes heat from the room by passing air over the indoor coil, whilst the waterside heat exchanger either adds or extracts heat from the water loop. If the supply temperature from the water loop is enough, the unit can work as a traditional fan-coil unit thanks to the 3 intake fans installed above the heat exchanger.
Image/scheme	

Technical and operational parameters

Integration type	Emission with generation unit inside
Heating/ Cooling system type	Mechanical Compression Heat Pump
Dimensions (mm)	742×160×672
Weight (kg)	36
Max thermal power (kW)	1.1
Efficiency (%)	n.a.
Efficiency class	n.a.

COP	4.31
EER	4.32
Acoustic rating (dB)	n.a.

Control system

Control type	Local control
Sensor type	Temperature sensor
Communication protocol	Wi-fi, narrowband

Architectural values

Integration impact	Modern aesthetic, therefore difficult to integrate
Visibility	High indoor, Minimal outdoor (two holes)
Reversibility	Medium: it requires two holes in the masonry, leaving traces in case of uninstallation
Conservation compatibility	The aesthetic is not compatible with historic context; however, it could exploit the existing plumbing system

Commercialisation

Technology Readiness Level	TRL 8
Investment cost	€€€
Operational cost	€€

Sustainability

GHG emission (operational)	+++
GHG emission (embedded)	++

Pros and cons

Pros	The system is able to provide heating and cooling by replacing the existing radiators
	It integrates a small-size DC compressor to increase the thermal power coming from the centralized generation system (preferably low temperature heat pump), according to the energy demand of each room. This allows to minimize heat losses on the existing distributions pipes (water temp. <30°C in winter and >15° in summer), to avoid condensation in cooling mode and to increase the COP/EER of the centralized heat pump. The same compressor provides dehumidification when needed
	It allows the drainage of the condensation directly in the existing heat distribution pipes, avoiding connection of the units to the building drainage system
	It allows to provide mechanical ventilation with heat recovery, by means of small vents to be realized on the external wall attached to the fan-coil
	It is equipped with a low-speed and low-noise fan and has a compact design
Cons	

2.2.4. Trench fan coil

General information

☒	☒	☐

Product type	Trench fan-coil
Brand name	Clima Canal - Jaga
Source website	https://www.jaga-canada.com
Description	It is a fan coil unit designed for low-temperature water operation that allows for simultaneous heating and cooling. It was designed for in-floor installation, and the cooling is very effective with both sensible and total cooling systems.
Image/scheme	

Technical and operational parameters

Integration type	Emission
Heating/ Cooling system type	Hydronic heating and cooling
Dimensions (cm)	Variable
Weight (kg)	Variable
Max thermal power (kW)	Variable
Efficiency (%)	n.a.
Efficiency class	n.a.
COP	n.a.
EER	n.a.
Acoustic rating (dB)	45

Control system

Control type	n.a.
Sensor type	n.a.
Communication protocol	n.a.

Architectural values

Integration impact	Medium: built in existing floor, so finishing should be removed + piping placed.
Visibility	Low: only a grill for air inlet and outlet is visible.
Reversibility	Medium: can be removed from the floor easily, floor should be replaced.
Conservation compatibility	Higher thermal power in combination with low temperature heating. built-in in the floor so no visible heating elements in interior.

Commercialisation

Technology Readiness Level	TRL 9
Investment cost	€€
Operational cost	€

Sustainability

GHG emission (operational)	+
GHG emission (embedded)	- -

Pros and cons

Pros	Very quick-responding system and low temperatures possible and can be combined with ventilation.
Cons	Noise pollution.

2.2.5. Milled floor heating

General information

☒	☒	☐

Product type	Milled floor heating
Brand name	Thermoduct
Source website	https://www.thermoduct.be
Description	By milling the heating pipes into an existing concrete floor, a lower construction height is achieved. On top of the concrete slab (with heating pipes), only a finishing layer is needed. With the support of the heat pump, this system can be used for both heating and cooling. This system reacts very quickly (with limited thermal activation). Heat is lost through the bottom of the floor if no insulation is installed.
Image/scheme	

Technical and operational parameters

Integration type	Distribution, emission
Heating/ Cooling system type	Hydronic heating and cooling
Dimensions (cm)	Variable
Weight (kg)	Variable
Max thermal power (kW)	Variable
Efficiency (%)	-
Efficiency class	-
COP	-
EER	-
Acoustic rating (dB)	-

Control system

Control type	Thermostats
Sensor type	Temperature
Communication protocol	n.a.

Architectural values

Integration impact	Low: When milling in an existing concrete floor, there is no integration impact. Floor height is not changed
Visibility	Low: there is nothing visible of the heating system
Reversibility	Low: once milled it cannot be undone
Conservation compatibility	Perfect solution for heating spaces where there is already a concrete screed present. Floor finishing should be removed first and replaced afterwards, can damage original floor

Commercialisation

Technology Readiness Level	TRL 9
Investment cost	€€
Operational cost	€

Sustainability

GHG emission (operational)	+
GHG emission (embedded)	n.a.

Pros and cons

Pros	No impact on construction height and quick-responding system.
Cons	Heat dispersion.

2.2.6. Thin dry radiant surface system

General information

☒	☒	☐

Product type	Radiant dry floor system
Brand name	Kilma Futura - RBM
Source website	https://rbm.eu/en/futura
Description	It is a radiant heating system specifically designed to be installed above the screed, which is why it is referred to as "dry." The system consists of insulating panels that allow heat to be distributed evenly from the bottom to the top. Heated or cooled water can circulate through the pipes, and the required thickness is only 30 mm.
Image/scheme	

Technical and operational parameters

Integration type	Distribution, emission
Heating/ Cooling system type	Hydronic heating and cooling
Dimensions (mm)	Thickness 30 mm
Weight (kg)	Variable
Max thermal power (kW)	-
Efficiency (%)	-
Efficiency class	-
COP	-
EER	-
Acoustic rating (dB)	-

Control system

Control type	Thermostatic
Sensor type	Temperature
Communication protocol	n.a.

Architectural values

Integration impact	Medium: require work on the entire surface to be heated, but the thickness is reduced.

Visibility	Low: there is nothing visible of the heating system
Reversibility	Medium: This is a dry system, so removed.
Conservation compatibility	Enhancing the thermal mass of a dry underfloor heating without high ring the floor buildup dramatically.

Commercialisation

Technology Readiness Level	TRL 9
Investment cost	€€€
Operational cost	€

Sustainability

GHG emission (operational)	+
GHG emission (embedded)	- - -

Pros and cons

Pros	Enhanced thermal mass without high construction height. Very low thickness. Speed and ease of installation
Cons	High investment costs.

2.2.7. PCM and underfloor heating

General information

☒	☒	☐

Product type	PCM and underfloor heating
Brand name	Pluss savE® HS25 HDPE underfloor PCM panels - Plussat
Source website	https://plussat.eu
Description	PCM consists of substances that can absorb and release energy during a phase transition without changing temperature. Floor heating can heat up during the night and release heat during the day. Conversely, solar power during the day can be used in a heat pump to heat the PCM and release it during the evening and night.
Image/scheme	

Technical and operational parameters

Integration type	Distribution, emission
Heating/ Cooling system type	Hydronic heating and cooling
Dimensions (cm)	n.a.
Weight (kg)	n.a.
Max thermal power (kW)	n.a.
Efficiency (%)	n.a.
Efficiency class	n.a.
COP	n.a.

EER	n.a.
Acoustic rating (dB)	n.a.

Control system

Control type	n.a.
Sensor type	Temperature
Communication protocol	Wi-Fi

Architectural values

Integration impact	Medium: the construction height is limited but still higher than existing height (due to the PCM/insulation board).
Visibility	Low: there is nothing visible of the heating system
Reversibility	High: This is a dry system, so easily removed.
Conservation compatibility	Enhancing the thermal mass of a dry underfloor heating without high ring the floor buildup dramatically.

Commercialisation

Technology Readiness Level	TRL 9
Investment cost	€€€
Operational cost	€

Sustainability

GHG emission (operational)	+
GHG emission (embedded)	- - -

Pros and cons

Pros	Enhanced thermal mass without high construction height.
Cons	Hydrocarbon and salt hydrate PCM are expensive and bad for the climate. Leaking is a possible risk.

2.2.8. Hydronic active insulation

General information

Heating ☒	Cooling ☐	Ventilation ☒

Product type	Hydronic active insulation (Building envelope on low temperature heating)
Brand name	WarmBuilding - WarmBouwen
Source website	https://warmbouwen.nl
Description	WarmBuilding is a technique that prevents heat loss through the facade while bypassing the drawbacks of interior insulation. It maintains the original moisture and temperature-regulating properties of the existing wall. The facade is open to vapor, aiding in summer cooling. A finely distributed piping system keeps the wall's temperature between 16 and 20 ℃ year-round. An inner insulation layer prevents interior heat from being lost to the cooler facade. This design minimizes transmission loss in winter and facilitates heat collection in summer. Heat can be sourced from the sun, air, ground, or low-temperature heat pumps.
Image/scheme	 

Technical and operational parameters

Integration type	Distribution, emission
Heating/ Cooling system type	Hydronic heating and cooling
Dimensions (cm)	n.a.
Weight (kg)	n.a.
Max thermal power (kW)	n.a.
Efficiency (%)	n.a.
Efficiency class	n.a.
COP	n.a.
EER	n.a.
Acoustic rating (dB)	n.a.

Control system

Control type	n.a.
Sensor type	n.a.
Communication protocol	n.a.

Architectural values

Integration impact	Low: the nets are very thin and can be integrated in a plaster layer.
Visibility	Low: there is nothing visible of the heating system
Reversibility	Low: whole plaster layer should be removed.
Conservation compatibility	Without adding insulation (which have an integration impact) the transmission losses are reduced. Lower temperature systems are possible.

Commercialisation

Technology Readiness Level	TRL 9
Investment cost	€
Operational cost	€€

Sustainability

GHG emission (operational)	+
GHG emission (embedded)	-

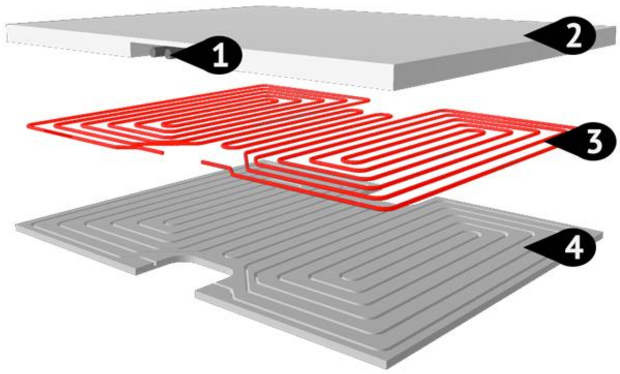
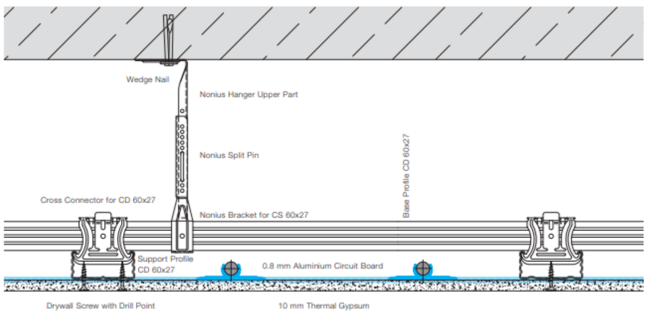
Pros and cons

Pros	Very small construction height/thickness and low temperature heating is possible.
Cons	Second heating system thus higher energy use?

2.2.9. Radiant ceiling with plasterboard finishing

General information

☒	☒	☐

Product type	Radiant ceiling with plasterboard panels
Brand name	ECOwall Dry - Rossato
Source website	https://www.rossatogroup.com
Description	It is a pre-assembled plasterboard radiant system designed for wall and ceiling heating and cooling. A modular system ready for installation, it adapts to any square footage. The pipework is made of PE-Xa, allowing water to circulate for both heating and cooling.
Image/scheme	 

Technical and operational parameters

Integration type	Distribution, emission
Heating/ Cooling system type	Hydronic heating and cooling
Dimensions (cm)	Variable
Weight (kg)	Variable
Max thermal power (kW)	-
Efficiency (%)	-
Efficiency class	-

COP	-
EER	-
Acoustic rating (dB)	-

Control system

Control type	Thermostat
Sensor type	Temperature
Communication protocol	n.a.

Architectural values

Integration impact	Medium: high impact on the ceiling but no or minor impact elsewhere.
Visibility	Low: in the room above there is nothing visible, the ceiling itself is finished with plaster so it blends in with the rest of the interior.
Reversibility	High: This is a dry system, so easily removed.
Conservation compatibility	It is versatile in that we can choose a wall or ceiling if the floor has constraints. The thickness is not excessive and does not affect the size of the rooms.

Commercialisation

Technology Readiness Level	TRL 9
Investment cost	€€€
Operational cost	€€

Sustainability

GHG emission (operational)	++
GHG emission (embedded)	-

Pros and cons

Pros	Not excessive overall dimensions. Quick installation time.
Cons	Little experience on true efficiency. You have to have very qualified installers.

2.2.10. Ceiling mounted floor system

General information

☒	☒	☐

Product type	Innovative solution
Brand name	
Source website	
Description	Instead of applying an underfloor heating system on top of the floor structure, as is done in most cases, the underfloor system is mounted on the ceiling of the space beneath the space that needs heating. After the installation of the underfloor heating system, an insulation layer should be applied, to make sure that the heat is transferred upwards.
Image/scheme	

Technical and operational parameters

Integration type	Distribution, emission
Heating/ Cooling system type	Hydronic heating and cooling
Dimensions (cm)	Variable
Weight (kg)	Variable
Max thermal power (kW)	-
Efficiency (%)	-
Efficiency class	-
COP	-
EER	-
Acoustic rating (dB)	-

Control system

Control type	Thermostat
Sensor type	Temperature
Communication protocol	n.a.

Architectural values

Integration impact	Low: when applied to the ceiling of a room with no valuable elements, there is almost no impact. It is placed against the existing ceiling, nothing is removed.
Visibility	Low: in the room above there is nothing visible, in the room beneath, it can be finished with any material.
Reversibility	High: This is a dry system, so easily removed.
Conservation compatibility	It is a low impact solution to introduce underfloor heating in valuable interiors because nothing changes in these spaces.

Commercialisation

Technology Readiness Level	TRL 6
Investment cost	€€€
Operational cost	€

Sustainability

GHG emission (operational)	+
GHG emission (embedded)	++

Pros and cons

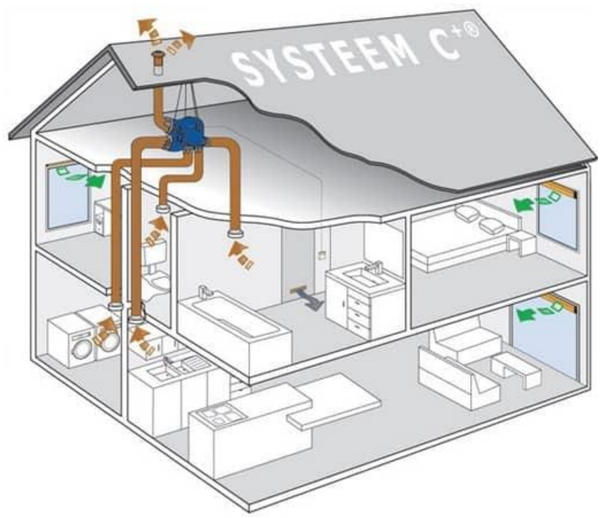
Pros	The radiant flux emitted is not affected by the furniture displacement.
Cons	No activation of the thermal mass. No knowledge about the effects on the historical wooden beams and finishing so far.

3. VENTILATION SYSTEMS

3.1. Nominal mechanical exhaust ventilation

General information

☐	☐	☒

Product type	BE Nominal exhaust ventilation
Brand name	multiple
Source website	-
Description	By depressurizing a structure with mechanical extraction of exhaust air, the fresh supply air from outside is pulled into the structure, trough deliberated ventilation openings (trickle vents) or through the building envelope. Exhaust air is extracted in the rooms with a lot of moisture and pollution productions, the 'wet' rooms (bathrooms, kitchen, laundry, …). Fresh air is drawn in the living zones, or 'dry' rooms. Intermediate zones ensure the transit of air.
Image/scheme	 https://sdvtechnics.com/ventilatiesystemen/systeem-c/

Technical and operational parameters

System type	Exhaust
System configuration	Centralized
Flow type	Variable
Heat recovery	No

Humidity recovery	No
Dimensions (cm)	n.a.
Weight (kg)	n.a.
Design flow rate (m^3/s)	From standard
Energy performance	No heat recovery but only one fan
Acoustic performance (dB)	Risk of noise pollution through vents

Control system

Control type	Local control
Sensor type	CO2 sensors, occupancy sensors and RH-sensors
Communication protocol	n.a.

Architectural values

Integration impact	Every 'dry' room needs ventilation vents connected to the exterior, which cause a high impact. The integration of ducts for the exhaust in every 'wet' room also have a high impact/
Visibility	Grills above windows/in facade are very visible. Vents at the interior side are also visible.
Reversibility	Intrusion through the building envelope/windows is difficult to reverse. Integration of vertical ducting is difficult to erase (cut-through levels), horizontal ducting and vents can be removed if not integrated in walls/ceiling/floors.
Conservation compatibility	A lot of windows need to be adjusted and/or cut-throughs in the facade need to be made, difficult when those elements have historical value. Also, the integration of the ducting inside is difficult to reconcile with valuable elements.

Commercialisation

Technology Readiness Level	TRL 9
Investment cost	€
Operational cost	€€

Sustainability

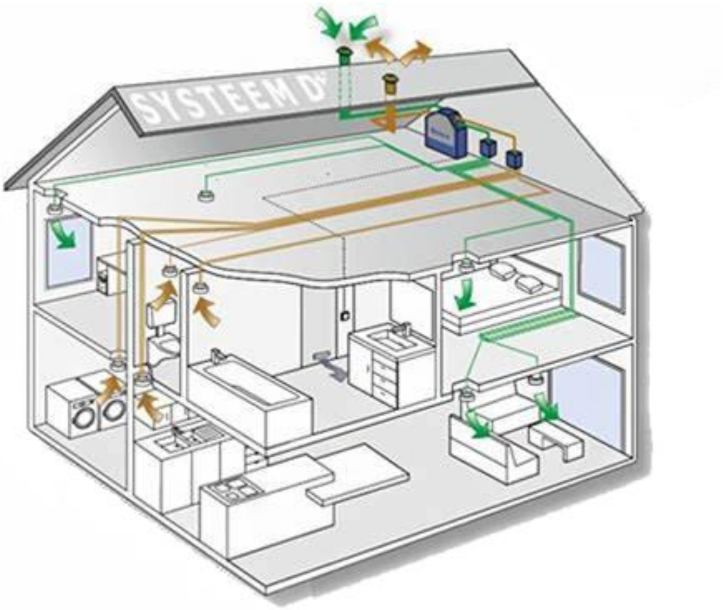
GHG emission (operational)	+++
GHG emission (embedded)	+

Pros and cons

Pros	Simple and well-developed system that guarantees a good IAQ.
Cons	Risk of noise pollution and draught caused by fresh supply air. No heat recovery possible.

3.2. Nominal mechanical ventilation with heat recovery

General information

☐	☐	☒
Product type		BE Nominal balanced ventilation with heat recovery
Brand name		multiple
Source website		-
Description		Mechanical supply and extraction of air ensures a good change of the interior air without pressurizing the building. It typically consists of two fans with two ducting networks. A heat exchanger can transfer the heat from the warm exhaust air to the cold supply air. Exhaust air is extracted in the rooms with a lot of moisture and pollution productions, the 'wet' rooms (bathrooms, kitchen, laundry, …). Fresh air is supplied to the living zones, or 'dry' rooms. Intermediate zones ensure the transit of air.
Image/scheme		 https://sdvtechnics.com/ventilatiesystemen/systeem-d-d/

Technical and operational parameters

System type	Balanced
System configuration	Centralized
Flow type	Variable
Heat recovery	Yes
Humidity recovery	Yes
Dimensions (cm)	n.a.
Weight (kg)	n.a.

Design flow rate (m^3/s)	From standard
Energy performance	Heat recovery, two fans
Acoustic performance (dB)	No sound from outside

Control system

Control type	Local control
Sensor type	CO2 sensors, occupancy sensors and RH-sensors
Communication protocol	n.a.

Architectural values

Integration impact	Only two connections with the outside (often through the roof). The integration of ventilation ducts in almost every room has some impact and design should be well considered.
Visibility	Ducting and vents can be visible in almost every room.
Reversibility	Integration of vertical ducting is difficult to erase (cut-through levels), horizontal ducting and vents can be removed if not integrated in walls/ceiling/floors.
Conservation compatibility	The integration of the ducting inside is difficult to reconcile with valuable elements. In the case of balanced ventilation, almost in every room a vent and ducting is needed.

Commercialisation

Technology Readiness Level	TRL 9
Investment cost	€€
Operational cost	€

Sustainability

GHG emission (operational)	+
GHG emission (embedded)	++

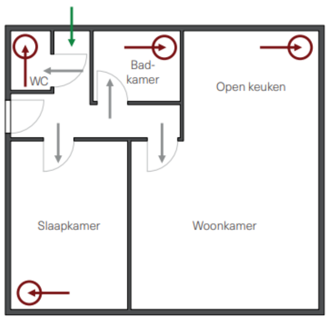
Pros and cons

Pros	Simple and well-developed system that guarantees a good IAQ. Heat recovery possible.
Cons	Need for a lot of ducting.

3.3. Central hall-based

General information

☐	☐	☒

Product type	C/D hall central
Brand name	No brand – Innovative idea (Buildwise)
Source website	https://www.buildwise.be
Description	Only one supply point for fresh air (provided with or without fans) is located in the central hallway. Mechanical extraction of polluted air is installed in every room, contrary to traditional systems that only have mechanical exhaust in the 'wet rooms.' From the central hallway, fresh air is drawn into the rooms by the negative pressure from the mechanical extraction.
Image/scheme	  

Technical and operational parameters

System type	Exhaust
System configuration	Centralized
Flow type	Variable
Heat recovery	No
Humidity recovery	No
Dimensions (cm)	n.a.

Weight (kg)	n.a.
Design flow rate (m^3/s)	From standard
Energy performance	No heat recovery but only one fan
Acoustic performance (dB)	No sound from outside

Control system

Control type	Local control
Sensor type	CO_2 sensors, occupancy sensors and RH-sensors
Communication protocol	n.a.

Architectural values

Integration impact	Only one place with natural ventilation opening (hallway) instead of every room. Higher number of ducts for extraction than in traditional exhaust systems
Visibility	Grill in front door is very visible
Reversibility	integration of vents and ducting is difficult to erase, same for ventilation opening in front door
Conservation compatibility	The biggest part of the (historic) windows is not touched, only in the front door a ventilation opening is placed. Every room needs an exhaust opening and ductwork (which is more than in a traditional exhaust system), so here the integration is more difficult in combination with heritage values

Commercialisation

Technology Readiness Level	TRL 7
Investment cost	€
Operational cost	€€

Sustainability

GHG emission (operational)	++
GHG emission (embedded)	++

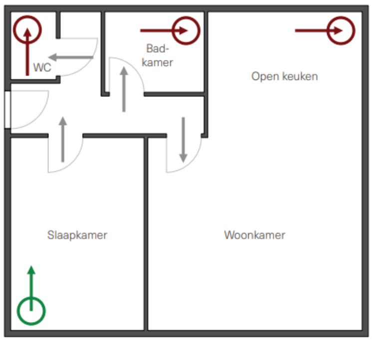
Pros and cons

Pros	Air quality is good. All rooms except for the central hallway have low draught risk and have low noise risk for sounds originating outside.
Cons	Higher total design building airflow rates. Hallway has high ventilation heat losses with more risk on draught.

3.4. Cascade mechanical ventilation with heat recovery

General information

☐	☐	☒

Product type	D-cascade
Brand name	No brand – Innovative idea (Buildwise)
Source website	https://www.buildwise.be
Description	Mechanical extraction is utilized in the living room, kitchen, and bathroom, while fresh air is supplied only in the bedrooms. Fresh air flows from the bedrooms to the living rooms through the hallway. This setup relies on the different times of use in bedrooms and living rooms.
Image/scheme	 

Technical and operational parameters

System type	Balanced
System configuration	Centralized
Flow type	Variable
Heat recovery	Plate heat recovery
Humidity recovery	Can be possible
Dimensions (cm)	n.a.

Weight (kg)	n.a.
Design flow rate (m^3/s)	From standard
Energy performance	Low because heat recovery
Acoustic performance (dB)	Less than traditional because less grilles

Control system

Control type	Both possible, preference for local control
Sensor type	CO2 sensors, occupancy sensors and clock
Communication protocol	n.a.

Architectural values

Integration impact	Lower than traditional balanced system because less ductwork and the use of the hall as flow-through space. Still relatively high because of the needed ducts
Visibility	Only grills are visible
Reversibility	Integration of ducts is difficult to erase
Conservation compatibility	Only one ventilation point per room (instead of two in traditional balanced systems) or no specific ventilation point necessary. This means les ductwork so better for the heritage conservation. Contrary, there is still need for a lot of ducts, so this will be difficult to bring in compliance with heritage. No window grills

Commercialisation

Technology Readiness Level	TRL 7
Investment cost	€€
Operational cost	€

Sustainability

GHG emission (operational)	++
GHG emission (embedded)	++

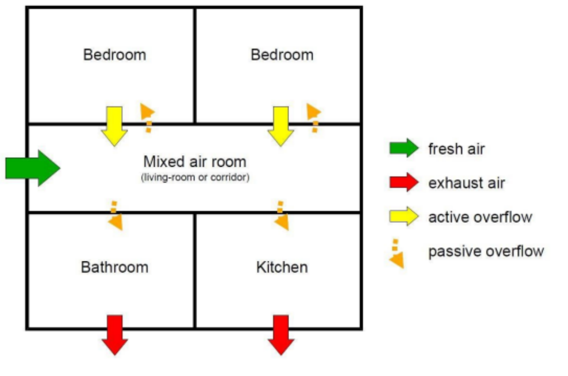
Pros and cons

Pros	Air quality is good, use of the building does not change Lower total design building airflow rates
Cons	Relies on typical occupation pattern to achieve good air quality.

3.5. Active overflow system

General information

☐	☐	☒

Product type	Active overflow System
Brand name	No brand – Innovative idea (Alexander Rieser UIBK)
Source website	https://www.tool.hiberatlas.com
Description	Fresh air is supplied by the central ventilation system in the distribution space (corridor/living room). By active transfer (fans) through walls or doors, fresh air is transported to living rooms. Through passive overflow openings, the air flows back to the mixing room (in non-airtight buildings the other way around). Exhaust fans in wet rooms extract the air to the central ventilation system. Due to the under pressure, the air from the mixing rooms is drawn into those wet rooms through passive overflow openings.
Image/scheme	

Technical and operational parameters

System type	Balanced
System configuration	Centralized
Flow type	Variable
Heat recovery	Recovery (probably)
Humidity recovery	Can be possible
Dimensions (cm)	n.a.
Weight (kg)	n.a.
Design flow rate (m^3/s)	n.a.
Energy performance	low because heat recovery. More individual fans, so maybe higher here
Acoustic performance (dB)	

Control system

Control type	n.a.
Sensor type	n.a.
Communication protocol	n.a.

Architectural values

Integration impact	Low impact because of the lack of ducts (only for supply in central room and exhaust). There have to be made openings in walls/door, so that causes a higher impact.
Visibility	The overflow openings can be maneuverer away aesthetically. The present ducts are more visible, but limited to a few (less important) spaces
Reversibility	Holes are made in walls and doors, so less reversible. The limited amount of ductwork is a benefit above traditional systems
Conservation compatibility	Due to the lower number of ducts and the possibility to make subtle overflow openings, this system is suited for heritage buildings. The holes can be problematic if there are parts of the interior protected

Commercialisation

Technology Readiness Level	TRL 7
Investment cost	€
Operational cost	€€

Sustainability

GHG emission (operational)	++
GHG emission (embedded)	+

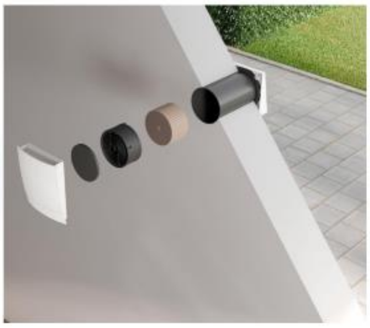
Pros and cons

Pros	Everything can be used as normal. The fans and openings are dampened. The system is difficult to have control over. Every room is supplied and exhausted with air.
Cons	Risky in less airtight buildings. When actively blowing in air into rooms, the moist warm air can be pushed through the construction (with interior insulation often) and can cause hygrothermal problems. Better is to actively remove the air to the mixing room, and passively supply the room with fresh air. In townhouses, the spaces are often very open and large, which makes the implementation of such system more difficult.

3.6. Decentralised ventilation with heat recovery system

General information

☐	☐	☒

Product type	Decentralised ventilation with heat recovery system
Brand name	X-well - Kermi
Source website	https://www.kermi.com
Description	Decentralized system with a ventilator that alternately supplies and exhausts air from the room. The internal heat exchanger captures heat from the exhaust and reuses it when air is supplied. Two push-pull systems are needed per room to ensure good air circulation.
Image/scheme	 

Technical and operational parameters

System type	Balanced
System configuration	Delocalized
Flow type	Variable
Heat recovery	Yes
Humidity recovery	No
Dimensions (cm)	20×20 (length variable)
Weight (kg)	-
Design flow rate (m^3/s)	From standard
Energy performance	Class A
Acoustic performance (dB)	35

Control system

Control type	Local control
Sensor type	VOC, humidity, and temperature sensors
Communication protocol	

Architectural values

Integration impact	Very high: to ventilators are placed for each room through the outer facade (only possible when facade is not valuable)

Visibility	High: The ventilator is small (20cmx20cm) but visible in outer facade
Reversibility	Difficult: the intervention is very local, but you make a hole in the building
Conservation compatibility	Because the decentralized ventilation system, no ducts are needed so this way it is very suitable for heritage buildings. The intrusion in the outer wall makes this solution less suitable

Commercialisation

Technology Readiness Level	TRL 9
Investment cost	€€
Operational cost	€

Sustainability

GHG emission (operational)	+
GHG emission (embedded)	++

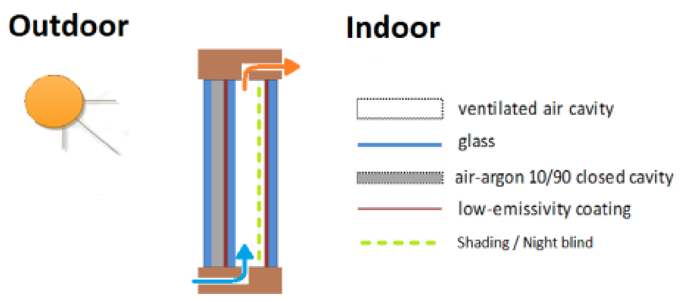
Pros and cons

Pros	Good indoor air quality
Cons	A lot of noise pollution. Control by user is difficult.

3.7. Ventilation system with window

General information

☐	☐	☒

Product type	Ventilation system with window
Brand name	No brand – Innovative idea (ClimaWin)
Source website	https://www.hiberatlas.com
Description	This innovative ventilation system is built into a window and operates in three distinct modes: Winter Mode: Fresh air enters the window from the bottom, where it gets pre-heated by sunlight in the gap between the two glass panes before being released into the room at the top. Summer Mode: An external air curtain is established, which minimizes solar heat gain to the interior by utilizing the ventilated space between the glass, resulting in no ventilation. Bypass Mode: In this mode, there is no preheating, and outside air directly flows in (in conjunction with Option 2). The system does not require ductwork or fans; however, mechanical exhaust remains necessary.
Image/scheme	 7

Technical and operational parameters

System type	Mechanical/natural
System configuration	Centralized
Flow type	Variable
Heat recovery	Not in strict sense of the concept. But can go up to 125%
Humidity recovery	No
Dimensions (cm)	-
Weight (kg)	-
Design flow rate (m^3/s)	-
Energy performance	Can reduce ventilation heat losses with up to 65%. Total energy saving up to 20% %
Acoustic performance (dB)	40 dB

Control system

Control type	Local
Sensor type	Humidity, temperature, CO2, occupancy sensors
Communication protocol	

Architectural values

Integration impact	Very high; this is a whole window, so if there are historic important windows, this option cannot be implemented.
Visibility	High: the appearance of an historic window is not possible.
Reversibility	The window can be replaced easily.
Conservation compatibility	This solution is for buildings where the facade (and the windows) is not of great heritage value, but the interior is. This way the ductwork and fans are omitted, while providing a good IAQ.

Commercialisation

Technology Readiness Level	TRL 6
Investment cost	€€€
Operational cost	n.a.

Sustainability

GHG emission (operational)	0
GHG emission (embedded)	+++

Pros and cons

Pros	Manual override is possible. Windows can still be opened. Comfort is better because no risk of draught.
Cons	More risk of pollution and sound coming into the building.

3.8. Decentralised ventilation for monumental buildings with a protected facade

General information

☐	☐	☒

Product type	Decentralised ventilation for monumental buildings with a protected facade
Brand name	Silenzio Retro ZR - DUCO
Source website	https://www.duco.eu
Description	It is a point ventilation system specifically developed for historic buildings with protected facades.
Image/scheme	

Technical and operational parameters

System type	Exhaust
System configuration	Centralized/delocalized
Flow type	Constant
Heat recovery	No
Humidity recovery	No
Dimensions (cm)	300 or 190
Weight (kg)	n.a.
Design flow rate (m^3/s)	0.013
Energy performance	-
Acoustic performance (dB)	43 dB acoustic dampening

Control system

Control type	n.a.
Sensor type	n.a.
Communication protocol	n.a.

Architectural values

Integration impact	High: a hole in the wall is made
Visibility	High: very visible on the exterior and interior

Reversibility	Low: a hole is made.
Conservation compatibility	Historicising ventilation grille could be approved by heritage authorities for natural air supply.

Commercialisation

Technology Readiness Level	TRL 9
Investment cost	€
Operational cost	0

Sustainability

GHG emission (operational)	0
GHG emission (embedded)	n.a.

Pros and cons

Pros	Way for natural supply with limited impact on the exterior
Cons	Ventilation grill so risk of noise pollution. Very visible at the interior side.

3.9. Roller shutter ventilation

General information

☐	☐	☒

Product type	Roller shutter ventilation
Brand name	Trasivent - Renson
Source website	https://www.renson.eu
Description	This ventilation system utilizes the shutter box. It does not affect the exterior appearance of the building in any way.
Image/scheme	  

Technical and operational parameters

System type	Exhaust
System configuration	Centralized
Flow type	Constant

Heat recovery	No
Humidity recovery	No
Dimensions (mm)	2200 – 60 - 91
Weight (kg)	n.a.
Design flow rate (m^3/s)	n.a.
Energy performance	-
Acoustic performance (dB)	44 dB

Control system

Control type	n.a.
Sensor type	n.a.
Communication protocol	n.a.

Architectural values

Integration impact	Low: only a hole in the roller blind casing is needed.
Visibility	Low: from the exterior nothing is visible, in the interior a metal plate is visible
Reversibility	Low: the hole is made, so difficult to undo
Conservation compatibility	When a roller blind case is present, this is a low impact way of providing air supply without touching the exterior view.

Commercialisation

Technology Readiness Level	TRL 9
Investment cost	€
Operational cost	0

Sustainability

GHG emission (operational)	0
GHG emission (embedded)	n.a.

Pros and cons

Pros	Possible to self-regulating and low impact.
Cons	Risk of noise pollution and draught

3.10. Window ventilation with heat recovery

General information

☐	☐	☒

Product type	Window mounted Push-Pull heat recovery ventilation
Brand name	Endura Twist - Renson
Source website	https://www.renson.eu
Description	It is a window vent that controls both the extraction and supply of air using a single device. Inside the device, the heat exchanger ensures that fresh outside air is preheated before being released into the room.
Image/scheme	 

Technical and operational parameters

System type	Balanced
System configuration	Delocalized
Flow type	Constant
Heat recovery	Yes
Humidity recovery	No
Dimensions (cm)	n.a.
Weight (kg)	n.a.
Design flow rate (m^3/s)	0.02
Energy performance	n.a.

Acoustic performance (dB)	40

Control system

Control type	n.a.
Sensor type	n.a.
Communication protocol	n.a.

Architectural values

Integration impact	Medium: placing a new window with this system is a high impact, but low impact for a decentral ventilation system.
Visibility	Low: vents are not visible from the exterior or interior, they are integrated in the dakuten of the window
Reversibility	Low: the whole window should be replaced.
Conservation compatibility	Integrating a low impact ventilation system with heat recovery. It imposes that the windows should be replaced so probably difficult in front facade

Commercialisation

Technology Readiness Level	TRL 9
Investment cost	€€
Operational cost	€

Sustainability

GHG emission (operational)	+
GHG emission (embedded)	n.a.

Pros and cons

Pros	Lower impact ventilation system (because no ducts).
Cons	Less efficient than central system and new windows needed.

3.11. Decentralised ventilation through the roof

General information

☐	☐	☒

Product type	3.1.9 Decentralised ventilation through the roof
Brand name	DucoMax ZR HD - DUCO
Source website	https://www.duco.eu
Description	It can be considered a trickle vent for a mechanical exhaust ventilation system with the special feature that it can be installed on a roof (with at least a 25% slope) beneath a special roof tile.
Image/scheme	 

Technical and operational parameters

System type	Exhaust
System configuration	Centralized/ delocalized
Flow type	Constant
Heat recovery	No
Humidity recovery	No
Dimensions (mm)	145
Weight (kg)	n.a.
Design flow rate (m^3/s)	0.017 - 0.028
Energy performance	n.a.
Acoustic performance (dB)	n.a.

Control system

Control type	n.a.
Sensor type	n.a.
Communication protocol	n.a.

Architectural values

Integration impact	Low: Only a hole in the roof structure is needed with big vent in the inside.
Visibility	Medium: Very visible from the inside, barely visible from the outside (only the ventilation roof tile)
Reversibility	Low: a hole in the roof is needed, not easily reconverted.

Conservation compatibility	When outside view is important, this is a good solution for a ventilation opening (attic interior is often less valuable).

Commercialisation

Technology Readiness Level	TRL 9
Investment cost	€
Operational cost	n.a.

Sustainability

GHG emission (operational)	0
GHG emission (embedded)	n.a.

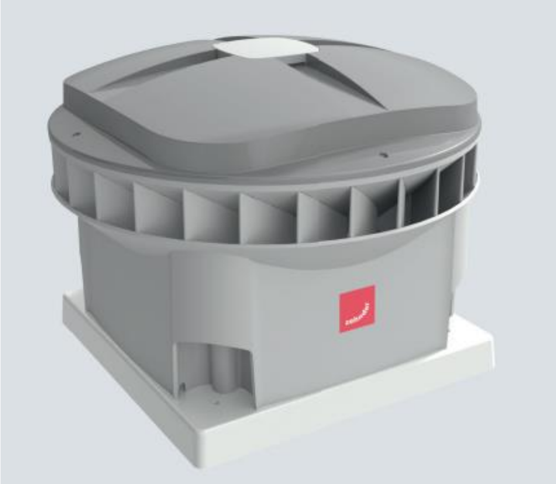
Pros and cons

Pros	Way for natural supply with limited impact on the exterior.
Cons	Ventilation grill so risk of noise pollution. Very visible at the interior side.

3.12. Roof ventilator

General information

Heating ☐	Cooling ☐	Ventilation ☒

Product type	Roof ventilator
Brand name	ComfoRoof MX - Zehnder
Source website	https://www.zehnder.be
Description	This ventilation system is installed on the roof of a building and provides fresh air to rooms with centrally controlled mechanical ventilation. The roof fan draws polluted air from the building through ducts. It is particularly suitable for large buildings.
Image/scheme	

Technical and operational parameters

System type	Exhaust
System configuration	Centralized
Flow type	Variable
Heat recovery	No
Humidity recovery	No
Dimensions (mm)	428 or Ø200
Weight (kg)	n.a.
Design flow rate (m^3/s)	0.097
Energy performance	n.a.
Acoustic performance (dB)	72

Control system

Control type	n.a.
Sensor type	n.a.
Communication protocol	n.a.

Architectural values

Integration impact	Low: when placed on existing chimney, higher when placed on the roof of annex
Visibility	High: visible from the outside, but on the roof.
Reversibility	High: placed on top of chimney, so can be removed.
Conservation compatibility	Easy way to implement mechanical exhaust without adding ventilation ducts when using the chimneys instead. No impact on the interior.

Commercialisation

Technology Readiness Level	TRL 9
Investment cost	€
Operational cost	€

Sustainability

GHG emission (operational)	+
GHG emission (embedded)	n.a.

Pros and cons

Pros	Easy way of enhancing the natural exhaust flows.
Cons	Ventilation grill so risk of noise pollution. Care must be taken to achieve an aesthetic result.

3.13. Floor based ventilation

General information

☐	☐	☒

Product type	Floor based ventilation
Brand name	HiberAtlas
Source website	https://www.tool.hiberatlas.com
Description	Classical mechanical ventilation system with the distribution ductwork integrated in the floor. The ventilation ducts are integrated together with the hydraulic system in a concrete layer between thermal and sound insulation.
Image/scheme	 

Technical and operational parameters

System type	Balanced
System configuration	Centralized
Flow type	Variable

Heat recovery	Yes
Humidity recovery	Can be possible
Dimensions (cm)	n.a.
Weight (kg)	n.a.
Design flow rate (m^3/s)	n.a.
Energy performance	n.a.
Acoustic performance (dB)	n.a.

Control system

Control type	n.a.
Sensor type	n.a.
Communication protocol	n.a.

Architectural values

Integration impact	High: the floor must be refurbished.
Visibility	Low: when the floor is finished, there is no sign of the ducts. Only the ventilation openings are visible
Reversibility	Very difficult: the ducts are integrated in the floor (concrete), so for reversing this measure, the floor has to be taken out
Conservation compatibility	This can be an interesting solution to implement a ventilation system when the ceilings and walls are very valuable

Commercialisation

Technology Readiness Level	TRL 9
Investment cost	€€
Operational cost	€

Sustainability

GHG emission (operational)	0
GHG emission (embedded)	0

Pros and cons

Pros	Low intrusive
Cons	This system could not be coupled with a radiant heating system.

3.14. Window Actuators

General information

☐	☐	☒

Product type	Window Actuators
Brand name	WMB 801 - Windowmaster
Source website	https://www.windowmaster.com
Description	Window actuators could be installed on existing windows to control ventilative cooling/intended natural airflow.
Image/scheme	

Technical and operational parameters

System type	Natural
System configuration	Centralized
Flow type	Variable
Heat recovery	No
Humidity recovery	No
Dimensions (cm)	277 x 45 x 42
Weight (kg)	1.1
Design flow rate (m^3/s)	n.a.
Energy performance	n.a.
Acoustic performance (dB)	n.a.

Control system

Control type	n.a.
Sensor type	n.a.
Communication protocol	n.a.

Architectural values

Integration impact	Modern aesthetic, therefore difficult to integrate
Visibility	High: motor and opening mechanism are very visible.
Reversibility	Medium: mechanism can be removed, the connection with the window could have caused some damage
Conservation compatibility	A solution with less impact for enhancing natural ventilation or ventilate cooling by controlling the opening behaviour of the windows.

Commercialisation

Technology Readiness Level	TRL 9
Investment cost	n.a.
Operational cost	0

Sustainability

GHG emission (operational)	0
GHG emission (embedded)	+

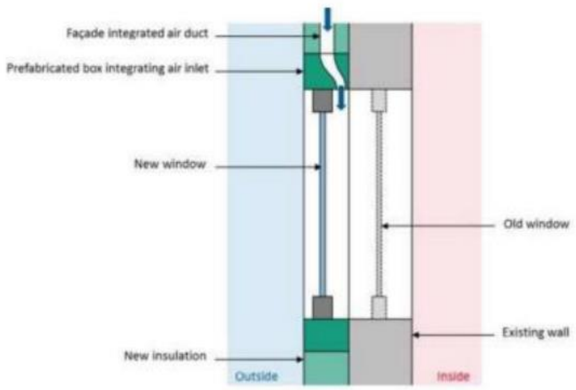
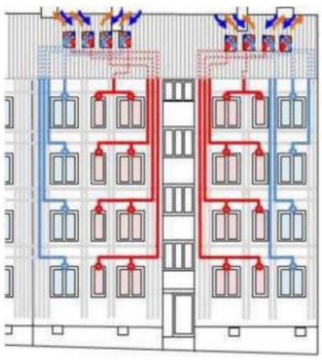
Pros and cons

Pros	They can make the whole building more efficient and autonomous. It is suitable for smoke ventilation.
Cons	Users lose the control over the windows.

3.15. Facade integrated ventilation ducts

General information

☐	☐	☒

Product type	
Brand name	
Source website	Hiberatlas
Description	When retrofitting outer walls, ventilation ducts can be placed in this new layer of insulation. New windows are placed more to the outside, so that the ventilation ducts can enter the interior behind the windows.
Image/scheme	  

Technical and operational parameters

System type	Balanced, Exhaust, Supply
System configuration	Centralized
Flow type	Variable
Heat recovery	Possible
Humidity recovery	Possible
Dimensions (cm)	n.a.
Weight (kg)	n.a.
Design flow rate (m^3/s)	n.a.
Energy performance	n.a.
Acoustic performance (dB)	n.a.

Control system

Control type	n.a.
Sensor type	n.a.
Communication protocol	n.a.

Architectural values

Integration impact	Medium: a thick insulation package is added which have a hight impact. The air ducts however have minimal impact on the interior side, except from a vent above the windows.
Visibility	Medium: the additional thickness is visible, the air ducts not.
Reversibility	Low: a whole insulation layer should be removed to be able to remove the air ducts.
Conservation compatibility	The less valuable back facade in Belgian townhouses is ideal to insulate with a thick new layer with air ducts included. The windows can be replaced in the same movement, so that the integration goes smoothly.

Commercialisation

Technology Readiness Level	TRL 9
Investment cost	€€
Operational cost	€

Sustainability

GHG emission (operational)	+
GHG emission (embedded)	++

Pros and cons

Pros	Integrating typical ventilation systems without interior impact.
Cons	Valuable facades are covered with insulation layer. Windows can be replaced, which can alter the overall view.

4. HVAC controls

Each HVAC system, regardless of the above category, is controlled in one way or another. The control can have a significant impact on the total performance of the system.

Advanced controls have the potential to achieve higher performance levels with regards to energy efficiency and achievable comfort, but they often require higher initial efforts and investment.

4.1. Control strategy categories

The operation of HVAC systems on a building level can be classified in five levels of control. The proposed classification is done based on the amount of information that is available to the control system and the extent to which it can flexibly control the HVAC system on a building level:

- 1-zone
- Zonal
- Central
- Central+
- Model Predictive Controls (MPC)

4.1.1. 1-zone

In residential HVAC systems, typically 1 central thermostat controls the heating and cooling system. The temperature sensor in the thermostat, sometimes combined with an outdoor temperature sensor, is used as input to a control algorithm that decides whether the pump that feeds the emission system is active or not. The building system is either on or off for all conditioned spaces. Further refinement of the heating emission power is optionally achieved by use of local analogue thermostatic valves.

For a mechanical ventilation system the most basic mode of control is a simple switch that allows the inhabitant to set select the mechanical ventilation airflow rates. This selection effects all ventilated spaces simultaneously. More advanced variations also exist that include sensors for e.g. presence, temperature, humidity, CO_2 to automatically change the mechanical ventilation airflow rates over time. Such systems still classify as 1-zone as the control algorithm will control all ventilated spaces simultaneously.

The controls of the heat-cold emission systems and ventilation systems are not coupled.

4.1.2. Zonal

A zonal control strategy is a strategy that applies the same principles of the 1-zone system but for subsections of the building. Doing so makes it possible to heat or cool different zones/rooms of the building on other moments in time. Each zone has its own thermostat and follows its own control algorithm. The control algorithm of one zone is not directly affected by the state of the other zone controls.

From a technical perspective such a control system needs actuators to effectively execute the zonal strategies. This can be done by use of e.g. different pumps or mechanical actuator valves.

A typical approach is to divide the building into a day- and a night-zone but a more advanced zonal control system is also possible where e.g. each room is considered a zone.

For ventilation, zonal controls are usually achieved by use of mechanical actuators that limit the airstream to the zones where a sensor monitors the indoor air quality to be bellow acceptable limits. In case of an MVHR system, the AHU is able to handle this and keep balanced airflow rates by use of local sensors.

The controls of the heat-cold emission- and ventilation systems are not expected to be coupled.

4.1.3. Central

An extension on the zonal system consists of a central overarching control that has a birds-eye view of the system and is able to make building level decisions.

For example, a central ventilation system control decides which zone to actively supply with fresh air based on the highest detected CO_2 level in the zones. The more local zone-control logic is thus overruled by the central unit at this point.

Another example is the case of a ventilation system where the IAQ is good in all spaces and the rooms should consequently all just be supplied by only 10% of the nominal flow rate. In this case is it best that all valves open completely and it is the central fan that lowers its ventilator speed to save energy. Such a control algorithm needs a central place where the different control actions are coordinated.

As these systems are often connected, central control systems are able to integrate external information like local weather data by use of web-API's.

The controls of the heat-cold emission- and ventilation systems are not expected be coupled here.

4.1.4. Central+

In the Central+ category, the information of the main technical systems is combined and transferred between systems to support more advanced control strategies. For example, if the CO_2 sensor in a bedroom does not detect someone sleeping in that room, the heating system lowers the set temperature.

Additionally, this can easily go beyond just the control of heating/cooling and ventilation by integrating other sources of information. For example, if window-state (open or closed) sensors are available due to the presence of a burglar alarm system, this information could be used to. While the window is open, the control knows not to actively ventilate that space and shut off the heating system during winter.

4.1.5. Model Predictive Controls (MPC)

Lastly, there is the category of model predictive controls. This way of controlling a system is technically speaking compatible with all levels of controls but is most sensible in combination with a Central or Central+ system.

MPC control extends such systems by using a model to continuously predict how a system would perform given different control actions. Based on the set of predictions, the model selects the best control action to execute. To perform these predictions on a system level, it needs information/estimates of future boundary conditions (e.g. weather predictions, estimated changes in outdoor particle concentrations.)

SHORTLISTS of HVAC solutions

5. Archetype shortlists

As previously introduced, the energy-conscious design of an HVAC system essentially relies on a virtuous relationship between the building and its surrounding context. Following this approach, for each region a brief overview of the locale climate is provided.

Based on the data reported, the most suitable HVAC concept for each archetype will be discussed.

The first step in refining a longlist is the definition of a robust and context-sensitive set of selection criteria. These criteria should reflect both the overarching goals of the retrofit—improving energy performance, user comfort, and operational efficiency—and the specific constraints imposed by the heritage status of the building. The key criteria to establish the shortlist include:

Technical Compatibility: Components must work effectively with the building's existing infrastructure, such as radiators, boilers, ductwork, or electrical systems.
Minimally Invasive Design: Given the need to preserve the structural and aesthetic integrity of a listed building, components should require minimal disruption to walls, floors, or ceilings. Solutions that can be retrofitted without significant masonry or structural interventions are prioritized.
Energy Performance and Efficiency: Components are assessed based on their potential to reduce energy consumption and enhance the overall efficiency of the HVAC system.
End-User Comfort: Comfort-related factors such as temperature consistency, air quality improvements, acoustic performance (low noise levels), and ease of control are critical.
Cost-Effectiveness: The total cost of ownership, including upfront costs, installation expenses, and long-term operational savings, is evaluated. Components with favourable payback periods are prioritized.
Visual and Aesthetic Impact: Components must integrate harmoniously into the historical context. This includes ensuring that visible elements, such as vents or wall-mounted units, are discrete or sympathetic to the building's design.
Regulatory Compliance: The shortlisted components should be preferable comply with local building regulations, heritage conservation guidelines, and energy codes, ensuring legal and operational feasibility. However, some advanced solutions are reported as well.

The retrofit solutions for the historical townhouses in every region are depended on this local climate and construction traditions. Therefore, the shortlist is drawn up for each region. As HVAC concepts are also tailored on the internal organisation, scale, heritage constraints and the type of construction that is considered, the shortlists are composed to hold the necessary systems for all archetypes of the region. Per region, a group of local experts in the necessary areas of expertise were brought together to discuss, argue and select the (combination of) systems to be part of the shortlist in light of the project ambitions and future work packages.

Firstly, an overview of the different HVAC concepts per archetype is given, after which these configurations are elaborated more in depth with their corresponding (dis)advantages. To conclude, a list of the concepts that will be researched is summarized, selecting from the longlist of solutions. Naturally, some concepts might be applicable for multiple archetypes and even for different regions.

5.1. Italy

5.1.1. Climatic and environmental condition

The climate in Mantua is typically continental, characterized by rather cold winters and hot summers. The trend of average temperatures in the cold season is not critical; however, the minimum values encountered require particular attention to thermal dispersion and the associated heating requirements, which are expected to be considerable.

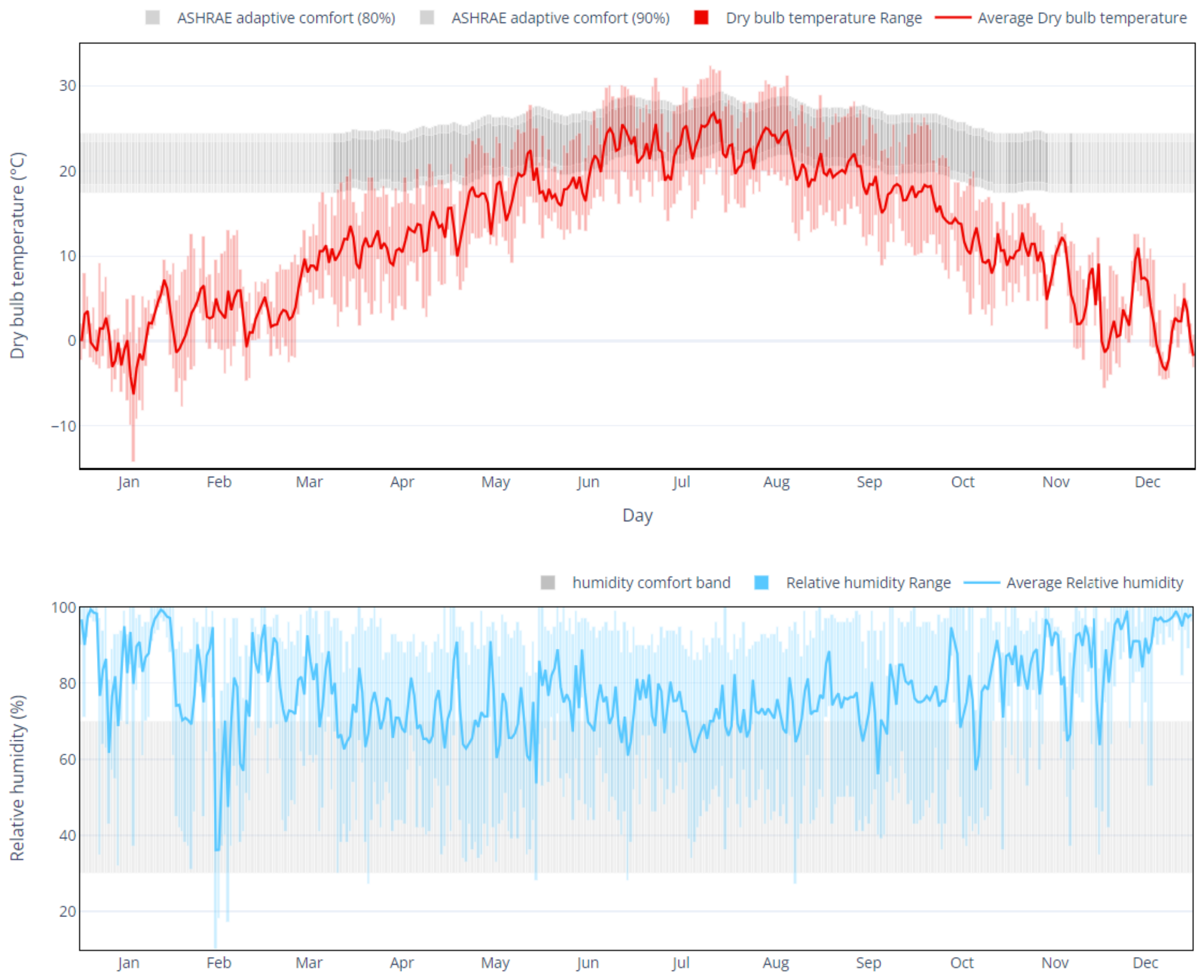


Figure 1 Average dry bulb temperature (top) and relative humidity (bottom) of Mantova (source: https://clima.cbe.berkeley.edu/).

In summer, the monthly average temperatures appear misleading, as they seem relatively mild. However, a detailed analysis of the hourly data reveals significant peaks that occur with notable frequency, accompanied by relatively high levels of humidity. Unfortunately, during the summer, the windiness of the site appears to be rather limited, so removing heat (both sensible and latent) through natural ventilation is difficult to implement, unless artificial effects are created locally to slightly increase wind speed.

5.1.2. HVAC concept selection

Due to the different constrains of archetypes selected in Italy, the HVAC proposal prioritizes the minimization of masonry and plumbing works to enable reuse of existing systems, while aiming to improve energy efficiency and generate energy savings. It places particular emphasis on end-user comfort.

Thus, one of the core principles in retrofitting such buildings is the prioritization of reuse. Existing systems, such as ductwork, plumbing, and electrical wiring, are often preserved and adapted to support modern HVAC technology. For instance, by upgrading insulation or seals in existing pipes and ducts, it is possible to enhance the efficiency of heating and cooling systems without compromising the building's fabric. Similarly, modern HVAC controls, which often use wireless communication, can integrate seamlessly with existing electrical layouts, minimizing the need for structural modifications.

Energy saving can be achieved through innovative yet unobtrusive measures. Water loop solutions are particularly suitable for such buildings because they can often connect to existing radiators or underfloor heating systems. This avoids the need for extensive plumbing alterations. Beyond heating and cooling, ventilation plays a critical role in energy performance. Installing mechanical ventilation with heat recovery (MVHR) allows for improved air quality and thermal efficiency even if, often it requires new holes in the structure.

Emission units able to guarantee both thermal and acoustic comfort, also considering the visual impact, must be considered. Evenly distributed heating or cooling can be achieved using low-profile solutions like slimline fan-coil units or radiant panels. These systems deliver effective temperature control while maintaining a low visual profile, preserving the building's aesthetic.

In such respect, four different options have been outlined according to a different level of visual impact, called Low impact option, Low impact+ventilation, Medium Impact option, Hight impact option.

It should be noted that, all the solutions can be generally integrated with ventilative cooling strategies offering a solution to address both cooling and indoor air quality (IAQ) challenges in buildings. These strategies can work independently or in combination with mechanical systems to enhance energy efficiency, reduce cooling demands, and improve occupant comfort. For example the use of automated window actuators, or similar technologies, able to control the airflow based on real-time indoor and outdoor conditions, can always be considered. These actuators can be programmed to open windows during cooler periods, such as evenings or early mornings, to allow natural air circulation to lower indoor temperatures. This passive approach reduces the reliance on mechanical cooling systems, conserving energy and lowering operational costs. Additionally, window actuators can be linked to IAQ monitoring systems, ensuring windows open when pollutant levels exceed acceptable thresholds. This dual functionality addresses both thermal comfort and air quality, creating a healthier indoor environment. By strategically integrating such system, buildings can amplify this effect, creating efficient passive cooling with minimal energy input.

System Configuration: low impact option

To reduce the invasive intervention on the building, the existing radiators will be replaced with WLHP INNOVA hydronic radiators for heating. Such system, however, is also able to provide cooling if the generation system coupled with it is able to discharge the heat. In such regards the distribution of domestic water and heating/cooling from the technical room to individual apartments will utilize existing flues and/or walkways, taking advantage of current systems in each apartment based on existing boiler locations. Due to landscape and urban constraints of the subject buildings, implementing a controlled mechanical ventilation system is not feasible, as it would compromise the aesthetic integrity of both the facade and interior.

Advantages

This planned proposal introduces a range of features that significantly enhance both energy efficiency and operational convenience, making it a modern and practical solution for buildings. The integration of Water-Loop Heat Pump (WLHP) fan coil units provides dual functionality, allowing the system to seamlessly deliver both heating and cooling. This flexibility makes it suitable for year-round use, catering to the heating demands of winter and the cooling needs of summer without requiring separate systems for each function. The fan coils, placed strategically in individual rooms, ensure localized comfort by allowing precise temperature adjustments, thereby enhancing the overall thermal environment of the building.
A particularly innovative feature of this system is the year-round circulation of water at a stable temperature range, typically between 20 and 30°C. This approach not only ensures consistent performance but also prevents condensation on uninsulated pipes during the summer.
Another key advantage is the reuse of the existing piping system in the building. By adapting the current infrastructure, the system avoids the need for extensive renovations or new installations. This ability to use the same network for both heating and cooling greatly simplifies the retrofit process, minimizing disruption and reducing costs. It also ensures that the system can be integrated into buildings with historical or architectural constraints, where significant alterations to the structure may not be feasible.
The WLHP system further optimizes water temperature, allowing efficient heating or cooling tailored to individual room requirements.

Limitations

The proposed system, while efficient and versatile, does present certain challenges that should be carefully considered during planning and implementation. One key requirement is the need for electrical connections for each Water-Loop Heat Pump (WLHP) fan coil unit, which may necessitate additional wiring and infrastructure work, particularly in retrofit scenarios. After that such scenario do not allow to control automatically the air quality in the different zones.
Another consideration is the necessity of condensate drain connections for each fan coil to ensure proper operation during cooling mode. These drains are essential to manage the

moisture extracted from the air and prevent water buildup, which could otherwise compromise system performance or cause damage.
The system also has a heat output limitation of 3.6 kW, which makes it suitable for spaces of approximately 25 square meters with a ceiling height of 3 meters. This constraint means that larger spaces may require additional units or supplementary heating solutions to maintain consistent comfort levels.
If the system is utilized for cooling and the pipes are not insulated, there is a risk of condensation forming on the surface of the pipes, particularly in humid conditions. This could lead to water damage or mold growth, undermining the system's benefits and potentially increasing maintenance needs. Proper insulation of the pipe network is therefore strongly recommended when the system is employed for cooling.
It should be noted that such solution cannot ensure proper Indoor Air Quality (IAQ), as it relies solely on operable windows controlled by the occupants to manage air exchange. While this approach allows for some degree of ventilation, it lacks the consistency and control required to maintain optimal air quality, especially in spaces with high occupancy or limited air movement.
The reliance on user-operated windows also introduces variability in air quality and ventilation effectiveness, as it depends on occupant behavior, external weather conditions, and the building's orientation. This lack of a systematic ventilation strategy may lead to poor IAQ, particularly during adverse weather or in urban areas with high levels of outdoor air pollution.
Moreover, this approach impacts the building's potential energy savings. Opening windows for ventilation disrupts the thermal balance maintained by HVAC systems, leading to energy losses during heating or cooling seasons. Without a controlled ventilation system, energy efficiency is compromised, as the building cannot optimize air exchange while preserving indoor temperature stability.

System Configuration: low impact option+ventilation

The abovementioned system could be further enhanced by integrating decentralized ventilation systems (active or passive) into the windows or shutters. This addition would complement the existing Water-Loop Heat Pump (WLHP) system by improving indoor air quality and providing targeted ventilation without requiring extensive ductwork. This solution is particularly effective in scenarios where updates to the fenestration or building envelope are permissible, as it allows for the seamless incorporation of ventilation units without requiring additional structural modifications.

Advantages

One of the primary benefits is the minimal structural intervention required. The decentralized ventilation system can be incorporated directly into windows or shutters, avoiding the need for extensive ductwork or alterations to the building's core structure. This makes them particularly suitable for retrofitting older or heritage buildings, where preserving the original architecture is essential.
Another advantage is the discreet integration that modern decentralized ventilation units offer. By embedding the ventilation components into windows or shutters, these systems can blend seamlessly into the building's design, maintaining aesthetic integrity. This is especially valuable for historically significant buildings or structures located in areas with strict architectural guidelines.
Decentralized ventilation systems also provide localized air exchange, allowing fresh air to enter individual rooms while expelling stale air. This enhances indoor air quality without

requiring a centralized ventilation network, making it a flexible solution for buildings with diverse space requirements or occupancy patterns.
The systems often incorporate energy-efficient heat recovery technology, which reduces energy loss during ventilation. By recovering heat from outgoing air and transferring it to incoming air, they contribute to energy savings and improved thermal comfort for occupants.
Another key advantage is the flexibility in installation. These systems can be added during window replacements or envelope upgrades, aligning with broader renovation efforts. This reduces overall project complexity and cost while ensuring a cohesive approach to building improvement.
Additionally, decentralized ventilation systems are independent of large mechanical systems, simplifying maintenance and operation. Their compact design allows for easier access and localized servicing, reducing long-term maintenance costs.
Lastly, these systems are often well-suited for buildings with limited space for traditional HVAC infrastructure. By eliminating the need for bulky ducts or centralized equipment, decentralized units maximize usable space within the building.

Limitation
A primary limitation is the dependency on the feasibility of window or envelope replacement. This solution is most practical when there are no regulatory or conservation constraints preventing modifications to the building's fenestration. In heritage buildings or structures with protected architectural features, replacing windows or altering the building envelope may not be allowed, making it challenging to implement this system without violating preservation guidelines.
Another challenge is the impact on aesthetics and design compatibility. While modern decentralized ventilation units can be discreet, integrating them into windows or shutters requires careful design to ensure they do not detract from the building's visual integrity. In historically significant buildings, even minor alterations to the appearance of windows can be subject to strict scrutiny, potentially limiting the applicability of this solution.
Additionally, technical constraints may arise during installation. For example, existing window frames might lack the structural capacity to accommodate ventilation units, requiring significant modifications or complete replacement. This can increase the complexity and cost of the project, especially in buildings where the envelope or windows were not initially designed for such integration.
Another challenge is the limited air supply capacity of decentralized ventilation systems. These units are typically designed to provide small quantities of air to individual spaces, which may be insufficient for buildings with high ventilation demands or spaces with dense occupancy.

Finally, the cost implications can be significant, especially in large buildings with numerous windows. Replacing or modifying multiple windows to include ventilation systems can represent a substantial investment, which may not always align with budget constraints or project goals.

System Configuration: medium impact option

The previous configuration could be further implemented with a full controlled centralized mechanical ventilation system. It is possible to use existing flues or chimney shafts to install in-line extract fans for improved ventilation. These fans are minimally visible and do not

compromise the facade or interior design. Of course also the air discharge outlets should be carefully located to minimize visual impact. Options include:
Discreet placement on the roof, with terminals designed to mimic traditional chimney pots. Use of existing vents or openings on less visible facades. Integration into courtyard-facing walls or areas shielded from public view.

Advantages
Effective removal of moisture, odours, and pollutants contributes to a healthier and more comfortable indoor environment, reducing the risk of long-term issues like mold or damp.
By leveraging existing architectural features like chimneys and flues, the system remains almost entirely hidden from view both internally and externally.

Limitation
The most significant limitation of basic extract ventilation systems is their limited capability for active dehumidification. These systems primarily function by removing air containing moisture from the indoor environment but do not actively lower humidity levels through mechanical processes like those found in refrigerant-based dehumidifiers. Thus, during periods of high external humidity (e.g., in summer or rainy day), the system's ability to reduce indoor moisture is further diminished, as incoming replacement air may itself have a high moisture content. Moreover, without supplementary measures, areas with persistent moisture, such as bathrooms and kitchens, may still experience condensation and damp, which can lead to long-term damage to historic materials.

System Configuration: hight impact option
If the distribution pipes could be replaced, a radiant system could be installed in combination with the water loop system suggested in the previous options, or in combination with a traditional fan coil emission system. The radiant floor alone, in fact, is not able to balance (generally) losses of not insulated building. However, floor heating is able to guarantee a better comfort than other systems.

Advantages
The system provides gentle, radiant warmth that is particularly appreciated in colder months, creating a cozy indoor environment. Heat is evenly distributed across the floor surface, eliminating cold spots or drafts often associated with radiators or forced-air systems, guaranteeing a better comfort.

Limitations
The radiant floor is characterized by low heat emission, thus generally, is not able to balance the heat losses. Moreover, if the system is used for cooling service a dehumidification system must be also implemented. Of course, such system could affect also the hight and the weight of the slab, thus careful verification must be carried out. Some historic floors, in fact, may not support the additional weight of radiant heating components and screeds without reinforcement, requiring engineering assessments.

Shortlist

	Low impact option	Low impact option + ventilation	Medium Impact option	High impact cost
Ventilation	none	Decentralized ventilation on window or shutter	ventilation placed in chimney or ventilation stacks	VMC
Distribution	Existing distribution	Existing distribution	Existing distribution	New hydronic distribution system
Emission	WLHP INNOVA hydronic	WLHP INNOVA hydronic	WLHP INNOVA hydronic	Radiant floor
Control	Zonal	Zonal	Zonal	Zonal

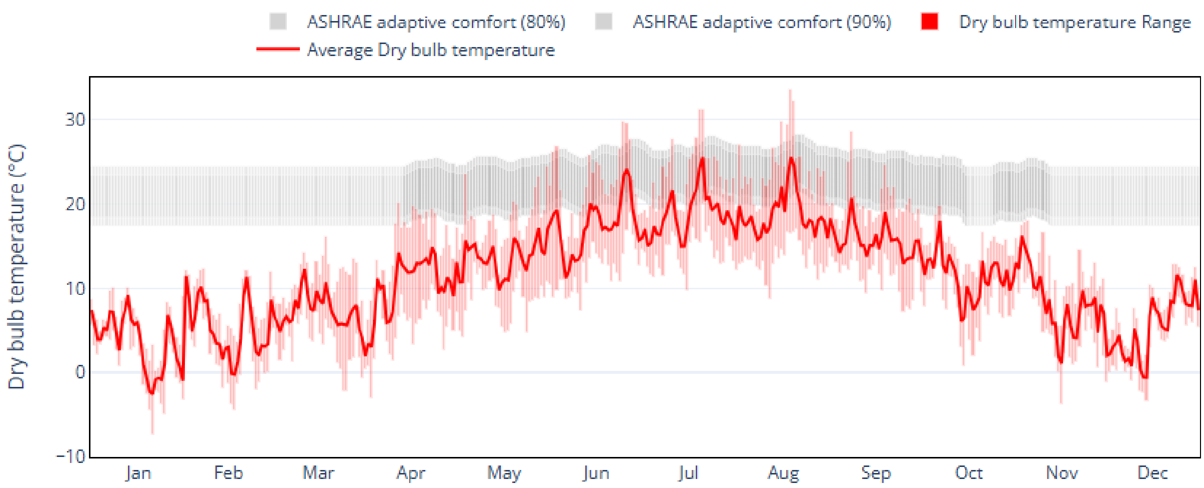
Table 1 Shortlisted solutions and scenarios for Italian archetypes.

5.2. Belgium

In Belgium, the composition of the shortlist and the set of investigated scenarios is composed by intensive consultation with the local partners. Experts from academia and practice were brought together in workshops to discuss the selection of possible solutions from the longlist. UGent prepared this workshops in close collaboration with the Urban Archaeology and Heritage Conservation Service of Ghent. During 4 live meetings the different possible strategies were discussed with SWECO-BE, GENT, KULEUVEN and BUILTWINS. The processing of this workshops was done by UGent and is provided in the following sections.

5.2.1. Climatic and environmental conditions

The climate in Ghent (and by extension in the rest of Belgium) is a temperate oceanic climate (class Cfb according to the Köppen climate classification), as present in most of West-Europe. The moderate climate in these regions is characterized by slightly cool and humid summers and relatively mild and rainy winters (caused by the influence of the sea) (Koninklijk Meteorologisch Instituut, n.d.). The average temperatures in winter rarely drop under 0°C and the average temperatures in summer rarely peak above 22°C. The difference between the seasons is relatively small, both in terms of dry bulb temperatures and relative humidity as in precipitation (Millison 2019).



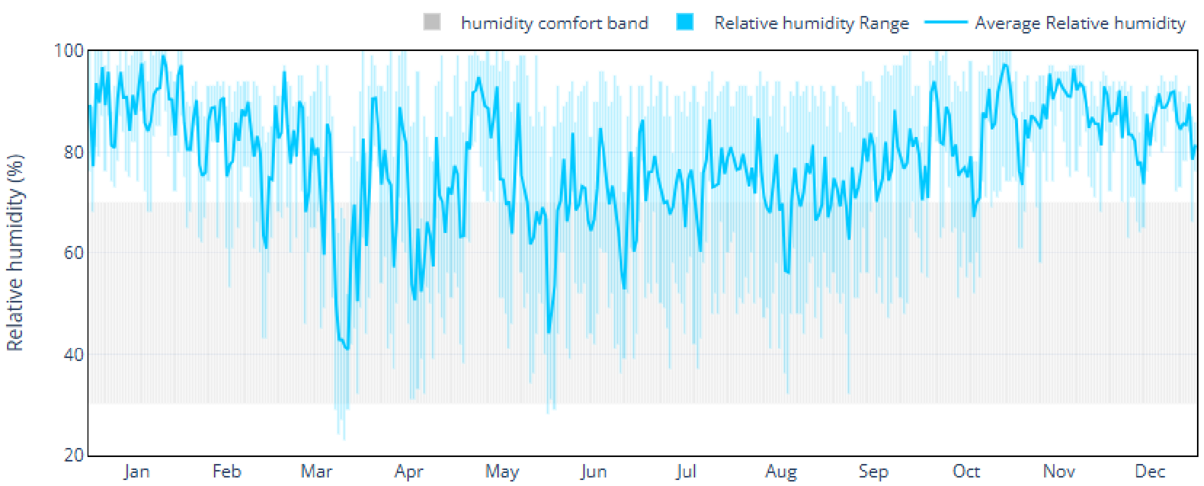


Figure 2 Average dry bulb temperature (top) and relative humidity (bottom) of Ghent (source: https://clima.cbe.berkeley.edu/).

The graphs presented above apply to Melle, a municipality situated in the border region of Ghent. As Melle is relatively rural, the temperatures recorded there do not precisely correspond with those of Ghent. Due to the Urban Heat Island effect, temperatures in the densely built and extensively paved urban areas of Ghent may, on average, be approximately 3°C higher than those in Melle, particularly during warm summer evenings (Maiheu et al. 2013).

5.2.2. Middle-class townhouse

Overview

Several options are constructed, each with their own configuration and respective set of (dis)advantages. The table below gives an overview of the concepts and the heating- and ventilation systems being used. Information concerning proposed controls and specific argumentation is provided in the dedicated paragraphs below the table. The different options are roughly ordered from least disruptive retrofit measure to most far-reaching measure (still in the context of heritage preservation).

All the listed heating emission concepts are selected to reflect the ambition to eliminate the use of fossil fuels. The investigated techniques make it possible to achieve the desired thermal comfort while still making the coupling with a low temperature heating production system (e.g. air-to-water heat pump). Options G till K make use of a hybrid heating and cooling system, each time with a different combination of emission components. These hybrid solutions are necessary to provide the desired thermal comfort with the given constraints in those scenarios. These specific heating configurations will be researched in a dedicated task within the project, T3.4.

Option	**Heat/Cold emissions system**										**Ventilation system**					**Control system**
	Use existing radiators	New LT radiators	Wall mounted fan coil	Trench fan coil	Typical radiant surface	Ceiling mounted FH	Thin dry radiant surface	Between floor joist FH	Radiant ceiling -plaster	Ventilation Air heater	MVHR	MEV	Central hall-based	Cascade MVHR	Active Overflow	
A - Preservation of space heating	X												X			Central +
B – Typical LT retrofit		X									X					1Z
C – Limited vertical disruption		X													X	Zonal
D - MEV ventilation			X									X				Central
E - No basement		X			X						X					1Z
F - Leveraging existing space heating 1	X					X							X			Central
G – Leveraging existing space heating 2*	X			X										X		Zonal
H – Leveraging existing space heating 3*	X									X	X					Central
I - Minimal heritage impact*			X			X								X		Zonal
J - Surface heating with constraints 1*	X							X							X	Zonal
K - Surface heating with constraints 2*								X		X	X					Central
L - Maximum surface heating (floor)							X						X			Zonal
M – Maximum surface heating (ceiling)									X		X					Zonal

*Hybrid heating

Table 2 List of option for middle-class townhouse in Belgium

HVAC concept selection

A - Preservation of space heating option

This HVAC solution makes maximum use of the existing emission and distribution systems for space heating and is coupled to a more innovative ventilation system: central hall-based. This ventilation system is not yet allowed in legislation nor in standards or guides for good practice. However, it has proven high potential in earlier simulation and pilot research projects (Caillou, Pecceu, and Van Gaever 2023).

System Configuration

The existing radiators are re-used (after repairs) and provide the necessary heating power even with a lower water supply temperature. Besides that, the existing distribution system for space heating can also be reused in its entirety.

It is possible that the existing radiators alone are not able to provide the necessary heating power. Therefore, the combination of the existing radiators with long-wave infrared heaters in also investigated in this configuration. This simple electric heating device could provide the needed extra heating power locally on colder days.

The ventilation system consists of one supply point of fresh air in the central hallway (which spans all the levels). The air could be provided by natural airflow through a ventilation opening in the facade, but preferably, the fresh air is mechanically provided to make use of a heat recovery system in the AHU. In all the other rooms, surrounding the hallway, mechanical exhaust is provided. The needed ventilation ducts can be integrated in the chimneys and in additional shafts in bathrooms and/or integrated in the new insulation package of the back facade.

Due to the limits of the existing radiators, a fine control system is needed to ensure a satisfying thermal comfort. Because of that, a central+ control system is applied, integrating information from the heating system, ventilation system, and other state sensors (e.g. opening of the windows) to provide adequate thermal comfort and IEQ.

Advantages

No alteration to the heating system is needed, so it is a fast and easy retrofit strategy and the re-use of the existing distribution system results in a lower impact. Low risk of discomfort linked to draught in the different rooms as the ventilation air is slightly conditioned in the central hall. Ventilation heat losses in each room - except for the hallway - are lower which limits the necessary design heating power output of the existing radiators, making this a viable option.

Limitation

Cooling the building is not possible when re-using the existing radiators. Additionally, the power output of the radiators is determined by their dimensions. This limitation could lead to somewhat higher supply temperatures than anticipated. The hallway could be affected by draught linked to the 'colder' supply air (when naturally provided) as the total building airflow is first provided to this central hallway. The ventilation system is not yet included in Belgian legislation.

B - Typical low temperature retrofit option

This HVAC option is frequently employed in typical renovations, focusing on proven technologies and legislation requirements. The system comprises of a nominal mechanical ventilation system with heat recovery as included in the Belgian EPB-legislation (ventilation system D). The existing radiators are replaced by new low temperature (LT) radiators to provide thermal comfort.

System Configuration

The existing emission system, comprising of 1970's radiators are replaced with new LT hydronic radiators so that it provides enough heating power when used at lower supply temperatures. The existing distribution system for space heating can presumably be reused in its entirety.

Regarding ventilation, the balanced air handling unit (AHU) is placed in the attic and is equipped with a plate heat exchanger for heat recovery. Fresh air supply is provided in the 'dry rooms' (living rooms, bedrooms, …) via the existing chimneys. Ventilation grilles in the wall of the chimney make the airflow possible. Exhaust air is extracted from the 'wet rooms' (kitchen, bathrooms, …). A dedicated technical shaft is placed to house ducting from the bathrooms. The ventilation duct from the kitchen located in the annex is integrated in the new insulation package of the back facade. The system control is '1-zone', where a central sensor controls the operation of the system as a whole.

Advantages

This system configuration is a well-known retrofit strategy, so it could be easily installed by normal contractors. Due to its simplicity, it is also a cost-efficient system. Re-use of the existing distribution system results in a lower impact.

Limitation

The hydronic LT radiators could be bigger than the existing radiators, resulting in a higher visible impact. The radiators cannot be used to cool. The nominal exhaust flow rates could be insufficient so additional exhaust could be necessary.

C - Limited vertical disruption option

This HVAC solution makes no use of the chimneys for vertical transport of ventilation or water distribution. Either because there are no chimneys, or because the existing chimneys are still in use when using a fireplace. Space heating is provided by low temperature (LT) radiators and an active overflow ventilation system is implemented.

System Configuration

The existing emission system, comprising of 70's radiators are replaced with new LT hydronic radiators so that it provides enough heating power when used on a lower water supply temperature. Consequently, the existing distribution system for space heating can presumably be reused in its entirety.

The active overflow ventilation system is a mechanical ventilation system with heat recovery where fresh air is supplied in the hallway, which spans all the levels. By active transfer (by means of fans) through walls or doors, the fresh air is transported to the living zones, which neighbour the hallway. Through passive overflow openings, the air flows back to hallway. The air is extracted in the bathroom and the kitchen through new shafts and facade integrated ventilation ducts to the AHU. In the same way, the air from the hallway is drawn into those wet rooms through passive overflow openings way due to the underpressure. A zonal control strategy is applied, to ensure that the active overflow system provides sufficient ventilation to each zone while maximizing the efficiency of the heating system for each zone separately.

Advantages

The retrofit of the space heating system is a well-known retrofit strategy, so it could be easily installed by normal contractors. Due to its simplicity, it is also a cost-efficient system. Also, re-using the existing distribution system results in a lower impact. Regarding the ventilation system, no ducting is needed in the living zones.

Limitation

Intrusions in doors or walls are needed for the active overflow ventilation system and the active pressurization could cause hygrothermal risks in combination with interior insulation. The hydronic LT radiators could be bigger than the existing radiators, resulting in a high visible impact and they cannot be used to cool. The ventilation system is not yet included in Belgian legislation.

D – MEV ventilation

This HVAC solution focusses on the implementation of a nominal natural air supply ventilation system, with mechanical exhaust (ventilation system C). This implies a higher impact on the building envelope. Space heating is provided by a convective heating system.

System Configuration

Integrating a natural air supply in combination with an improved airtightness (due to building envelope retrofit measures) without causing a negative impact on the building is a challenge. The natural air supply on the ground floor level can be guaranteed by the trickle vent integrated in the roller blind housing at streetside. Mechanical extraction of exhaust air in the kitchen in the annex. The ventilation ducts from the kitchen are integrated in the new insulation package of the back facade. On the other floors window trickle vents can be integrated in the new windows in the back facade. Mechanical extraction of exhaust air in the 'wet' rooms is through a dedicated ventilation shaft in the bathrooms. Air flows from the supply rooms to the exhaust rooms through the slits under interior doors or through new ventilation vents.
Regarding space heating, the existing radiators are replaced by fan coil units (ventilo-convectors). These fan coil units can provide a high power of heat (and cold) with a low water supply temperature using the active air displacement. The existing distribution system for space heating can presumably be reused in its entirety, keeping the impact low. A central control system is implemented, where actuators valves for both the heating and ventilation are included, allowing for high controllability on a central level.

Advantages

There is no ducting needed for air supply, only for exhaust. The ventilation concept is based per level, consequently this would be a suitable ventilation system for a situation where the multi-family townhouse is divided up in appartements per level. Additionally, the preservation of existing distribution system causes a lower impact.

Limitation

With MEV, there is no heat recovery possible. The direct natural air supply causes a risk of draught and noise pollution from outside through trickle vents. The noise of the fan coil units could be undesirable and should be considered in the design. this limitation could lead to somewhat higher supply temperatures than anticipated.

E - No basement option

This HVAC solution can be implemented when there is no basement, so when a slab on ground is present. A typical radiant surface system is implemented on the ground floor, low temperature (LT) radiators on the other floors. This configuration comprises of a nominal mechanical ventilation system with heat recovery as demanded by the Belgian EPB-legislation (ventilation system D).

System Configuration

The opportunity to dig out the soil beneath the ground floor gives rise to the implementation of a typical underfloor heating system in the living rooms (embedded in a concrete screed) after removing the existing wooden flooring. The floor level will not change because of the excavation. On the other floors, the existing emission system, comprising of 70's radiators are replaced by new LT radiators that provide enough heating power when used on a lower temperature. Consequently, the existing distribution system for space heating can presumably be reused in its entirety.
Regarding ventilation, the balanced air handling unit (AHU) is placed in the attic and is equipped with a plate heat exchanger for heat recovery. Fresh air supply is provided in the 'dry rooms' (living rooms, bedrooms, …) via the existing chimneys. Ventilation grilles in the wall of the chimney make the airflow possible. Exhaust air is extracted from the 'wet rooms' (kitchen, bathrooms, …). A dedicated technical shaft is placed to house ducting from the bathrooms. The ventilation duct from the kitchen located in the annex is integrated in the new insulation package of the back facade. The system control is '1-zone', where a central sensor controls the operation of the system as a whole.

Advantages

The thermal comfort will be high due to the evenly distributed heat through the underfloor heating. The floor heating on the ground floor could make use of the thermal mass of the screed. Additionally, cooling on the ground floor is possible with this configuration. Re-using parts of the existing distribution system results in a lower impact.

Limitation

The slow-responding heating system on the ground floor could make it more difficult to use sensitive control strategies. The hydronic LT radiators could be bigger than the existing radiators, resulting in a high visible impact. These radiators cannot be used to cool. The nominal exhaust flow rates could be insufficient so additional exhaust could be necessary.

F - Leveraging existing space heating 1 option

This HVAC option is the combination of the innovative central hall-based ventilation system with a radiant surface emissions system on the bel étage level and with the existing emission system on the other levels.

System Configuration

The ground floor (bel étage) is heated using surface radiant heating. Consequently, the existing emission and distribution system on this level are no longer used. A radiant surface heating system is placed on the ceiling of the basement, finished with a layer of insulation. On the other floors, the existing radiators are re-used (after repairs) and provide the necessary heating power even with a lower water supply temperature. On those levels, the existing distribution system for space heating can be reused in its entirety
The ventilation system consists of one supply point of fresh air in the central hallway (which spans all the levels). The air could be provided by natural airflow through a ventilation opening in the facade, but preferably, the fresh air is mechanically provided to make use of a heat recovery system in the AHU. In all the other rooms, surrounding the hallway, mechanical exhausts are provided. The needed ventilation ducts can be integrated in the chimneys and in additional shafts in bathrooms and/or integrated in the new insulation package of the back facade. A central control system is implemented, where actuators valves for both the heating and ventilation are included, allowing for high controllability on a central level.

Advantages
Low risk of discomfort linked to draught in the different rooms as the ventilation air is slightly conditioned in the central hall. Ventilation heat losses in each room - except for the hallway - are lower which makes sure that the power output of the existing radiators on a lower supply temperature and the radiant surface system are adequate.

Limitation
The hallway could be affected by draught linked to the 'colder' supply air (when naturally provided) as the total building airflow is first provided to this central hallway. The ventilation system is not yet included in Belgian legislation. Cooling is only possible on the ground floor.

G - Leveraging existing space heating 2 option
This HVAC solution makes maximum use of the existing emission and distribution systems for space heating, assisted by an additional convective heating system in a hybrid heating set-up. The ventilation system exists of cascade mechanical ventilation system with heat recovery (D-cascade) in the main building and a system with natural supply in the annex.

System Configuration
The existing radiators are re-used (after repairs) and provide heating power with a lower water supply temperature. When needed, the additional needed heating power is covered by trench fan coil units. This fan coil unit can be implemented when removing a small part of the wooden flooring. The existing distribution system for space heating can be reused in its entirety. Nonetheless, the new emission system needs a dedicated new distribution system, of which the vertical distribution can be placed in the chimneys.
The ventilation system is a cascade mechanical ventilation system with heat recovery. Instead of providing fresh supply air in all the dry rooms and exhaust in all the wet rooms, the setup is altered. Fresh air is supplied in the bedrooms through the chimneys and the exhaust air is extracted in the living rooms, kitchen and bathrooms through the chimneys again. The ventilation in the annex is considered as a separate system with natural fresh air supply through window trickle vents. This setup is possible because bedrooms and living rooms

have different times of use. A zonal control strategy is applied, where sensors in each zone control locally the amount of heating and ventilation that is needed.

Advantages

The trench fan coil units are not visible. The space heating system is a quick-responding system, ensuring a high controllability. A limited amount of ducting and intrusions is needed, only ducts in chimneys are required. The total ventilation supply airflow rate is lower, saving on ventilation energy losses.

Limitation

The power output of the trench fan coil units will be determined by the physical dimensions of the floor. Also, the noise of the fan coil units could be undesirable and should be considered in the design. The combination of these limitations could lead to somewhat higher supply temperatures than anticipated. A new distribution system for space heating/cooling is needed in addition to the existing. The ventilation system is not yet included in the Belgian standards.

H - Leveraging existing space heating 3 option

This HVAC solution strives to have the lowest visiam impact on the interior of the middle-class townhouse. It is a configuration that is suitable for high valuable interiors with decorated walls and ornamented ceilings. A hybrid system is implemented: the existing convective heating system is preserved in combination with an air-based system. A nominal balanced ventilation system as demanded by the Belgian EPB-legislation (ventilation system D) is implemented.

System Configuration

The existing distribution and emission system are preserved: the existing radiators are re-used (after repairs) and provide heating on lower water supply temperature. The radiators can provide in a base temperature and additional heating power can be covered by the preheated ventilation air, when needed. The air handling unit should consequently be served by the hydronic heating system. Fresh air supply is provided in the 'dry rooms' (living rooms, bedrooms, …) via the existing chimneys. Ventilation grilles in the wall of the chimney or in the mantelpiece make the airflow possible. Exhaust air is extracted from the 'wet rooms' (kitchen, bathrooms, …). A dedicated ventilation shaft is placed in the bathrooms and the ventilation ducts from the kitchen in the annex are integrated in the back facade insulation package. A central control system is implemented, where actuators valves for both the heating and ventilation are included, allowing for high controllability on a central level.

Advantages

This HVAC configuration ensures that there are no new emission systems visible in the rooms and that the existing ones are re-used. The combination of a slower responding heating system (radiators on low temperatures) with a quick-responding heating system (air) will aid in fine control strategies.

Limitation

The airflow is depended on the size of the chimneys and consequently heating through the ventilation air could be not the most efficient way of heating the building. The nominal exhaust flow rates could be insufficient so additional exhaust could be necessary. Additionally, the radiators cannot be used to cool.

I - Minimal heritage impact option

This HVAC solution could be used for a scenario where there is a lot of highly valuable elements in the facade and the interior that should be preserved and where a loss of original material is very undesirable. The ventilation system exists of cascade mechanical ventilation system with heat recovery (D-cascade) in the main building and a system with natural supply in the annex. Space heating is provided by a hybrid heating system consisting of a surface radiant emission system and convective heating (and cooling) to provide the needed thermal comfort.

System Configuration

A radiant surface heating system is placed on the ceiling of the basement, finished with a layer of insulation. This can provide in a base temperature and when needed, fan coil units can provide the additional heat power. The wall mounted fan coil units are integrated in the fireplace (or, alternatively, replacing the existing radiators). The fan coil units can provide a high power of heat (and cold) with a low water supply temperature using active air displacement. The distribution of the hot or cold supply water can happen in the existing chimneys. On the other levels, only fan coil units - replacing the radiators or also integrated in the chimneys - provide the space heating and cooling.
The ventilation system is a cascade mechanical ventilation system with heat recovery. Instead of providing fresh supply air in all the dry rooms and exhaust in all the wet rooms, the setup is altered. Fresh air is supplied in the bedrooms through the chimneys and the exhaust air is extracted in the living rooms. The kitchen and bathrooms are again extracted via the chimneys. The ventilation in the annex is considered as a separate system with natural fresh air supply through window trickle vents. This setup is possible because bedrooms and living rooms have different times of use. A zonal control strategy is applied, where sensors in each zone control locally the amount of heating and ventilation that is needed.

Advantages

The new emission systems are not visible any more in the room and the fireplace is restored to its original function: providing heat. A limited amount of ducting, and intrusions are needed, only ducts in chimneys are required. The total ventilation supply airflow rate is lower, saving on ventilation energy losses. On the ground floor, the thermal comfort will be high due to the evenly distributed heat via the underfloor heating, while on the other floors high controllability is achieved.

Limitation

The power output of the fan coil units will be determined by the physical dimension of the fireplace. Also, the noise of the fan coil units could be undesirable and should be considered in the design. The combination of these limitations could lead to somewhat higher supply temperatures than anticipated. The ventilation system is not yet included in the Belgian standards.

J - Surface heating with constraints 1 option

This HVAC solution strives to a maximal implementation of radiant surface emission systems, but without altering the interior of the dwelling, because of the constraints of a valuable interior. A hybrid system consisting of a radiant surface system and the existing radiators is implemented. An active overflow system is integrated to provide adequate ventilation.

System Configuration

Space heating is provided by a hybrid system consisting of underfloor heating (and cooling) and the existing radiators. An underfloor heating joist system is introduced, where the underfloor heating components are placed between the wooden beams of the floor structure, doing so the floor level is not increased. This necessitates removing the wooden flooring where needed and putting it back after installing the underfloor system. A new distribution system is needed for this emission system. The surface heating system can provide a base temperature and the existing radiators could guarantee the extra heating power when needed. The existing radiators are re-used (after repairs) and provide heating on lower water supply temperature.
The active overflow ventilation system is a mechanical ventilation system with heat recovery where fresh air is supplied in the hallway, which spans all the levels. By active transfer (by means of fans) through walls or doors, the fresh air is transported to the living zones, which neighbour the hallway. Through passive overflow openings, the air flows back to the hallway. The air is extracted in the bathroom and the kitchen through new shafts and facade-integrated ventilation ducts that lead to the AHU. Due to the underpressure, the air from the hallway is drawn into the wet rooms through passive overflow openings. A zonal control strategy is applied, to ensure that the active overflow system provides sufficient ventilation to each zone while maximizing the efficiency of the heating system for each zone separately.

Advantages
The thermal comfort will be high due to the evenly distributed heat through the underfloor heating. Additionally, cooling is possible with this configuration. The combination of a slow and more quick-responding system will aid in fine control strategies. Regarding the ventilation system, no ducting is needed in the living zones.

Limitation
Intrusions in doors or walls are needed for the active overflow ventilation system and the active pressurization could cause hygrothermal risks in combination with interior insulation. The wooden flooring needs to be removed where floor heating is placed which poses a risk of damaging the flooring. The ventilation system is not yet included in Belgian legislation.

K - Surface heating with constraints 2 option
This HVAC solution strives to surface heating, but with the constraints of a valuable interior. This results in a hybrid system of a radiant surface system in combination with an air-based system. A classic nominal balanced ventilation system as demanded by the Belgian EPB-legislation (ventilation system D) is implemented.

System Configuration
Space heating is provided by a hybrid system consisting of underfloor heating and the additional heating through preheated air. An underfloor heating joist system is introduced, where the underfloor heating components are placed between the wooden beams of the floor structure, prohibiting the floor level to increase. This necessitates removing the wooden flooring where needed and putting it back after installing the underfloor system. A new distribution system is needed for this emission system. The surface heating system can provide in a base temperature and additional heating power can be covered by the preheated ventilation air, when needed. The air handling unit should consequently be served by the hydronic heating system.
Regarding ventilation, the air handling unit is placed in the attic, providing heat recovery. Fresh air supply is provided in the 'dry rooms' (living rooms, bedrooms, …) via the existing

chimneys. Ventilation grilles in the wall of the chimney make the airflow possible. Exhaust air is extracted from the 'wet rooms' (kitchen, bathrooms, …). A dedicated ventilation shaft is placed in the bathrooms and the ventilation ducts from the kitchen in the annex are placed integrated in the new back facade insulation. A central control system is implemented, where actuators valves for both the heating and ventilation are included, allowing for high controllability on a central level.

Advantages

The thermal comfort will be high due to the evenly distributed heat through the underfloor heating. Additionally, cooling is possible with this configuration. The combination of a slow and more quick-responding system will aid in fine control strategies. No visible HVAC components in the rooms.

Limitation

The wooden flooring needs to be removed where floor heating is placed which poses a risk of damaging the flooring. The airflow is depended on the size of the chimneys and consequently heating through the ventilation air could be not the most efficient way of heating the building. The nominal exhaust flow rates could be insufficient so additional exhaust could be necessary.

L - Maximum radiant surface emission (floor) option

This HVAC system focuses on the maximum implementation of a radiant surface emission system, more specific underfloor heating (and cooling). This is only possible when the heritage context makes this possible (interior flooring is not valuable, or cannot be re-used, doors are not valuable, …). The maximum radiant surface emission implementation is paired with a more innovative ventilation system in this configuration: a central hall-based ventilation system.

System Configuration

A thin dry radiant surface system is implemented in each room except for the hallways, integrated above the wooden beams and under the wooden flooring. As this requires the wooden flooring to be replaced, the hollow floors of each level could be filled up with insulation material if needed. The floor level of the rooms will raise with a few centimetres resulting in a small step between the rooms and the hallways. The distribution system should be replaced, causing again a higher impact.

The ventilation system consists of one supply point of fresh air in the central hallway (which spans all the levels). The air could be provided by natural airflow through a ventilation opening in the facade, but preferably, the fresh air is mechanically provided to make use of a heat recovery system in the AHU. In all the other rooms, surrounding the hallway, mechanical exhaust is provided. The needed ventilation ducts can be integrated in the chimneys and in additional shafts in bathrooms and/or integrated in the new insulation package of the back facade. A zonal control strategy is applied, where sensors in each zone control locally the amount of heating and ventilation that is needed.

Advantages

The thermal comfort will be high due to the evenly distributed heat through the underfloor heating and cooling. Low risk of discomfort linked to draught in the different rooms as the ventilation air is slightly conditioned in the central hall. Ventilation heat losses in each room

- except for the hallway - are lower which limits the necessary design power output of the fan coil units and surface heating system. This configuration, with a maximum of radiant surface emission system ensures a high energy efficiency.

Limitation
Underfloor heating is used in wooden floors, which have a low thermal mass limiting the full potential of surface heating somewhat. The slower heating system, although quicker than conventional embedded surface heating, could make it more difficult to control 'in time' and use sufficient strategies. The hallway could be affected by draught linked to the 'colder' supply air (when naturally provided) as the total building airflow is first provided to this central hallway. The ventilation system is not yet included in Belgian legislation.

M - Maximum radiant surface emission (ceiling) option

This HVAC option is only possible when the ceilings are not valuable at all and should not be preserved. Radiant surface heating and cooling is integrated in a very impactful way and the ventilation system is a nominal mechanical ventilation system with heat recovery. The higher interior impact is a trade-off to allow a system suspected to achieve a high performance and good energy efficiency.

System Configuration
The building is heated (and cooled) using a radiant ceiling with plasterboard finishing. This system is placed under the existing ceiling and could be accompanied by additionally insulating the ceiling. The high ceiling heights help make this configuration possible. This setup results in a high impact on the interior (ceiling), so it can only be used when the ceiling (and the rest of the interior) has no ornaments, original materials or beautiful finishings. This configuration safeguards valuable floors or panelling. The new emission systems also necessitate a new distribution system.
In this configuration a mechanical ventilation system with heat is introduced. Integrating the heating system below the existing ceiling gives the opportunity to integrate some ventilation ducts and ventilation openings in this 'new' ceiling. New intrusions through existing floors and ceilings are needed to complete this ventilation setup. Fresh air supply is provided in the 'dry rooms' (living rooms, bedrooms, …), possibly through the chimneys. Exhaust air is extracted from the 'wet rooms' (kitchen, bathrooms, …). A dedicated technical shaft is placed to house ducting from the bathrooms. The ventilation duct from the kitchen located in the annex is integrated in the new insulation package of the back facade. A zonal control strategy is applied, where sensors in each zone control locally the amount of heating and ventilation that is needed.

Advantages
The thermal comfort will be high due to the evenly distributed heat through the ceiling system. The floor can be preserved in its original state and there are no emission systems visible. This configuration, with a maximum of radiant surface emission system ensures a high energy efficiency.

Limitation
Heating from the ceiling can cause some local thermal discomfort. The slower heating system, although quicker than conventional embedded surface heating, could make it more difficult to control 'in time' and use sufficient strategies.

Shortlist

	Technical solution (from longlist)
Heating (and cooling) emission systemzit ni	Use existing radiators (+ long-wave IR heating)
	New LT radiators
	Hydronic fan coil wall heating and cooling
	Trench fan coil
	Typical radiant surface system
	Ceiling mounted floor system
	Thin dry radiant surface system
	Water underfloor heating between joists
	Radiant ceiling with plasterboard finishing
	Ventilation Air heater
Hybrid heating (and cooling) concepts	Ceiling mounted floor system + Wall mounted fan coil
	Existing radiators + trench fan coil
	Existing radiators + Between Water underfloor heating between joists
	Water underfloor heating between joists + heating/cooling through ventilation air
	Existing radiators + heating/cooling through ventilation air
Ventilation concepts	Nominal mechanical exhaust ventilation (MEV)
	Nominal mechanical ventilation with heat recovery (MVHR)
	Central hall-based
	Cascade mechanical ventilation with heat recovery
	Active Overflow system
Ventilation components	Roller shutter ventilation
	Facade integrated ventilation ducts
Controls	1-zone
	Zonal
	Central
	Central+

Table 3 Shortlisted solutions and scenarios for middle-class townhouse in Belgium

5.2.3. Private mansion

Overview

Several options are constructed, each with their own configuration and respective set of (dis)advantages. The table below gives an overview of the concepts for space heating, cooling and ventilation being used. Information concerning proposed controls and specific argumentation is provided in the dedicated paragraphs below the table. The different options are again ordered from least disruptive retrofit measure to most far-reaching measure (still in the context of heritage preservation). Again, the proposed concepts make it possible to achieve the desired thermal comfort while still making the coupling with a low temperature heating production system (e.g. air-to-water heat pump).

Option	**Heat/Cold emissions system**					**Ventilation system**					**Control**
	Use existing radiators	Wall mounted fan coil	Trench fan coil	Ceiling mounted FH	Ventilation Air heater	MVHR	Decentral push-pull	Central hall-based	Cascade MVHR	Active Overflow	
A - Typical LT retrofit		X				X	X				1Z
B – Leveraging existing space heating*	X			X						X	Zonal
C – Minimal visual impact*			X		X				X		Central
D – hall-based T*	X	X	X	X				X			Central+

*Hybrid heating

Table 4 List of option for private mansion in Belgium

HVAC concept selection

A - Typical low temperature retrofit option

This HVAC option is frequently employed in typical renovations, focusing on proven technologies and legislation requirements. The system consists of a nominal mechanical ventilation system with heat recovery as included in the Belgian EPB-legislation (ventilation system D) where possible, supplemented by decentral push/pull ventilation where needed. Space heating (and cooling) is provided by convective heating (and cooling).

System Configuration

The existing radiators are replaced by fan coil units (ventilo-convectors). These fan coil units can provide a high power of heat (and cold) with a low water supply temperature using the

active air displacement. The existing distribution system for space heating can be reused in its entirety, keeping the impact low.
Replacing the fan coil units with water loop Hydronic radiators is also investigated in this configuration. This can be a more adequate solution when for example a central heat pump is not possible or the distribution losses would be too high. Decentral water-water heat pumps in each room, resembling classic radiators, ensure that the heat from the distribution system (water on very low temperatures) is used as a heat source for a separate Carnot cycle. Regarding ventilation, the balanced air handling unit (AHU) is placed in the attic and is equipped with a plate heat exchanger for heat recovery. Fresh air supply is provided in the 'dry rooms' (living rooms, bedrooms, …) via the existing chimneys. Ventilation grilles in the wall of the chimney make the airflow possible. Exhaust air is extracted from the 'wet rooms' (kitchen, bathrooms, …) through chimneys or dedicated shafts when possible. In rooms in the back of the building, which are not equipped with chimneys and where no shafts are possible, decentral push/pull units are implemented in the back facade to provide the necessary air change. The system control is '1-zone', where a central sensor controls the operation of the whole system.

Advantages

This system configuration is a well-known retrofit strategy, so it could be easily installed by normal contractors. Due to its simplicity, it is also a cost-efficient system. Additionally, the re-use of the existing distribution system results in a lower impact.

Limitation

Not all rooms are part of the balanced ventilation system, which could decrease the efficiency and controllability. The noise pollution of the push/pull ventilation components and the fan coil units could be undesirable.

B – Leveraging existing space heating option

This HVAC-solution strives to have almost no impact on the interior and exterior of the private mansion. Space heating is provided by a hybrid heating system of surface radiant emission system and the existing radiators on the ground floor. On the other levels, the existing radiators guarantee the needed thermal comfort. An active overflow ventilation system ensures the supply and exhaust of air.

System Configuration

The ground floor (bel étage) is heated and cooled using a surface radiant emission system. The floor system is placed on the ceiling of the basement, finished with a layer of insulation. A new distribution system is needed for this part. The surface heating system can provide in a base temperature on the bel étage and the existing radiators, which are often quite valuable in private mansions, could guarantee the extra heating power when needed. The existing radiators are re-used (after repairs) and provide heating on lower water supply temperature. On the other levels, the existing radiators are also re-used and provide the necessary heating power on a lower water supply temperature as the only heating system.
The active overflow ventilation system is a balanced mechanical ventilation system where fresh air is supplied in the hallway and the circulation space, which spans all the levels. By active transfer (by the means of fans) through walls or doors, the fresh air is transported to the living zones, which neighbour the hallway. Through passive overflow openings, the air flows back to hallway. The air is extracted in the bathroom and the kitchen through new

shafts and facade integrated ventilation ducts to the AHU. Due to the underpressure, the air from the hallway is drawn into those wet rooms through passive overflow openings. A zonal control strategy is applied, to ensure that the active overflow system provides sufficient ventilation to each zone while maximizing the efficiency of the heating system for each zone separately.

Advantages

On the bel-étage floor, the thermal comfort will be high due to the evenly distributed heat through the underfloor heating while on the other floors controllability is high. Also, re-using the existing distribution system results in a lower impact. Lastly, no ducting is needed in the living zones.

Limitation

Intrusions in doors or walls are needed for the active overflow ventilation system and the active pressurization could cause hygrothermal risks in combination with interior insulation. Additionally, the radiators cannot be used to cool.

C – Minimal visual impact option

This HVAC solution strives to have the lowest visible impact on the interior of the private mansion. It is a configuration that is suitable for high valuable interiors with decorated walls and ornamented ceilings, which are quite common in this archetype. The original cast-iron radiators, if present, can be left untouched and remain part of the interior decoration. The HVAC solution exists of a hybrid system of convective heating in combination with an air-based system. A cascade mechanical ventilation system with heat recovery provides adequate ventilation.

System Configuration

Trench fan coil units are provided in each room. This fan coil unit can be built in when removing some planks of the wooden flooring. The new emission system needs a dedicated new distribution system, of which the vertical distribution can be placed in the chimneys. This convective heating system can provide in a base temperature and additional heating power can be covered by the preheated ventilation air, when needed. The air handling unit should consequently be served by the hydronic heating system.
The ventilation system is a cascade balanced mechanical ventilation system (D-cascade). Instead of providing fresh supply air in all the dry rooms and exhaust in all the wet rooms, the setup is altered. The excess of rooms in the private mansion ensures that the time of use in the rooms is very different. Fresh air is supplied in one type of rooms through the chimneys and the exhaust air is extracted in other types of rooms (including kitchen and bathrooms) through the chimneys or new shafts. A central control system is implemented, where actuators valves for both the heating and ventilation are included, allowing for high controllability on a central level.

Advantages

This HVAC configuration ensures that there are no emission systems visible in the rooms (except for the ornamented radiators, which serve no function anymore). The system has a high controllability due to the quick-responding emission systems.

Limitation

The power output of the trench fan coil units will be determined by the physical dimensions of the floor. Also, the noise of the fan coil units could be undesirable and should be considered in the design. The combination of these limitations could lead to somewhat higher supply temperatures than anticipated. This new emission systems need a new distribution system. The ventilation system is not yet included in the Belgian standards.

D – Hall-based temperature option

This innovative option consists of a hall-based temperature concept in combination with a central hall-based ventilation system. This configuration is an innovative concept where the effectiveness should be researched thoroughly.

System Configuration

The hall-based temperature heating concept consists of a central hallway that serves as a hot core, with the adjacent rooms around it that need to be heated. The hallway, which forms the centre of the private mansion, is equipped with new and efficient emission systems (also in need of a new/altered distribution system) that can provide the needed heating power with low water supply temperatures. Surface heating and (trench) fan coil heating (possibly assisted by the existing radiators) can provide this 'core' heating. The heat is then transferred to the adjacent rooms by the ventilation system, a central hall-based system. The additional heating power can be provided by the existing radiators in those spaces, working on a lower water supply temperature.
The ventilation system consists of one supply point of fresh air in the central hallway and circulation space (which span all the levels). The air could be provided by natural airflow through a ventilation opening in the facade, but preferably, the fresh air is mechanically provided to make use of a heat recovery system in the AHU. In all the other rooms, surrounding the hallway, mechanical exhaust is provided. The needed ventilation ducts can be integrated in the chimneys and in additional shafts in bathrooms and in the insulation package of the back facade. Due to the strong interaction between the ventilation system and the heating system, a central+ control system is applied. Information from the heating system, ventilation system, and other state sensors (e.g. opening of the windows) is used to control alle the systems on a central level.

Advantages

In the living zones, which are often the most valuable zones, little to no interventions are needed. Due to the heating of the core, there is no risk of draught in the different rooms. Additionally, ventilation heat losses in each room - except for the hallway - are lower which limits the necessary design power output of the existing radiators, making this a viable option.

Limitation

The integration of new heat emission systems in the hallway have a high impact and it can be less efficient to heat up the core instead of the zones that actually need to be heated. The ventilation system is not yet included in Belgian legislation.

Shortlist

	Technical solution (from longlist)
Heating (and cooling)	Use existing radiators
	Hydronic fan coil wall heating and cooling

emission system	Trench fan coil
	Ceiling mounted floor system
	Ventilation Air heater
	Water loop Hydronic radiators wall heating and cooling
Hybrid heating (and cooling) concepts	Ceiling mounted floor system + use existing radiators
	Trench fan coil + heating/cooling trough ventilation air
Ventilation concepts	Nominal mechanical ventilation with heat recovery (MVHR)
	Central hall-based
	Cascade mechanical ventilation with heat recovery
	Active Overflow system
	Decentralised ventilation with heat recovery system
Ventilation components	Facade integrated ventilation ducts
Controls	1-zone
	Zonal
	Central
	Central+

Table 5 Shortlisted solutions and scenarios for private mansion in Belgium

5.2.4. Modest house

Overview

Several options are constructed, each with their own configuration and respective set of (dis)advantages. The table below gives an overview of the concepts for space heating and cooling and ventilation being used. Information concerning proposed controls and specific argumentation is provided in the dedicated paragraphs below the table. The different options are again ordered from least disruptive retrofit measure to most far-reaching measure (still in the context of heritage preservation). Again, the proposed concepts make it possible to achieve the desired thermal comfort while still making the coupling with a low temperature heating production system (e.g. air-to-water heat pump).

Option	**Heat/Cold emissions system**				**Ventilation system**				**Control**
	Use existing radiators	New LT radiators	Typical radiant surface system	Thin dry radiant surface	MVHR	MEV	Central hall-based	Cascade MVHR	
A – Preservation of space heating	X							X	Zonal
B - Typical LT retrofit		X	X		X				1Z
C – Surface heating with constraints*	X			X			X		Central
D – Maximum surface heating				X		X			Central+

*Hybrid heating

Table 6 List of option for modest house in Belgium

HVAC concept selection

A – Preservation of space heating option

This HVAC option focuses on a low impact on the interior of the building, with the maximum preservation of the existing systems. Space heating is provided by the existing radiators and a good indoor air quality is ensured by implementing a cascade mechanical ventilation system with heat recovery (D-cascade).

System Configuration

The existing distribution system is preserved and is used with water at a lower supply temperature. The existing radiators are re-used (after repairs) and provide the necessary heating power even with a lower water supply temperature.
The ventilation system is a cascade mechanical ventilation system with heat recovery. Instead of providing fresh supply air in all the dry rooms and exhaust in all the wet rooms, the setup is altered. Fresh air is supplied in the bedrooms through the chimneys and the exhaust air is extracted in the living rooms, kitchen and bathrooms through the chimneys again. This setup is possible because bedrooms and living rooms have different times of use. A zonal control strategy is applied, where sensors in each zone control locally the amount of heating and ventilation that is needed.

Advantages

No alteration to the heating system is needed, so it is a fast and easy retrofit strategy and the re-use of the existing distribution system results in a lower impact. The total ventilation supply airflow rate is lower, saving on ventilation energy losses.

Limitation

Cooling the building is not possible when re-using the existing radiators. Additionally, the power output of the radiators is determined by their dimensions. This limitation could lead to somewhat higher supply temperatures than anticipated. The ventilation system is not yet included in the Belgian standards.

B – Typical low temperature retrofit option

This option has the same configuration as option E of the middle class townhouse. Option E comprises the archetypical plan of the middle-class townhouse when there is no basement present, which resembles the modest house quite a lot, except for the extra floor level in the case of a middle-class townhouse.

C - Surface heating with constraints option

Space heating (and cooling) is provided by a hybrid system: the preservation of the existing radiators is accompanied by a radiant surface system on the ground floor. The efficiency of a combination with a more innovative ventilation system is tested in this configuration: a central hall-based ventilation system is implemented.

System Configuration

The existing emission- and distribution system are supplemented by a new system on the ground floor: a surface radiant heating system. By applying a thin dry underfloor heating system. The floor level will not raise drastically, as we can dig out this floor level. The surface heating system can provide a base temperature and the existing radiators could guarantee the extra heating power when needed. The existing radiators are re-used (after repairs) and provide heating on lower water supply temperature. On the other levels, the existing

radiators are also re-used to provide heat on a lower water supply temperature and function as the only heating system here.
The ventilation system consists of one supply point of fresh air in the central hallway (which spans all the levels). The air could be provided by natural airflow through a ventilation opening in the facade, but preferably, the fresh air is mechanically provided because it can make use of the heat recovery system. In all the other rooms, surrounding the hallway, mechanical exhaust is provided. The needed ventilation ducts can be integrated in the chimneys where they are present (and new shafts where needed). A central control system is implemented, where actuators valves for both the heating and ventilation are included, allowing for high controllability on a central level.

Advantages

The thermal comfort will be high due to the evenly distributed heat through the underfloor heating. Low risk of discomfort linked to draught in the different rooms as the ventilation air is slightly conditioned in the central hall. Ventilation heat losses in each room - except for the hallway - are lower which makes sure that the power output of the existing radiators on a lower supply temperature and the radiant surface system are adequate.

Limitation

The hallway could be affected by draught linked to the 'colder' supply air (when naturally provided) as the total building airflow is first provided to this central hallway. The ventilation system is not yet included in Belgian legislation. Cooling is only possible on the ground floor. Due to the dry underfloor system and the wooden floors, which have a low thermal mass, the full potential of surface heating is somewhat limited.

D - Maximum surface heating option

This HVAC option focuses on the maximum implementation of a radiant surface system, more specific underfloor heating and cooling. This is only possible when the heritage context makes this possible (less valuable flooring, walls, doors,…). A nominal mechanical exhaust ventilation system is implemented (C-system).

System Configuration

A thin dry radiant surface system is implemented in each room, except for the hallways, and integrated above the wooden beams and under the wooden flooring. As this requires the wooden flooring to be replaced, the hollow floors of each level could be filled up with insulation material if needed. The floor level of the rooms will raise with a few centimetres resulting in a small step between the rooms and the hallways. The distribution system should be replaced, causing again a higher impact.
Integrating a natural air supply in combination with an improved airtightness (due to building envelope retrofit measures) without causing a too high impact on the building is a challenge. The natural air supply on the ground floor level can be guaranteed by the trickle vent integrated in the roller blind housing at streetside. Mechanical extraction of exhaust air will be applied in the kitchen in the annex. The ventilation ducts from the kitchen are integrated in the new insulation package of the back facade. On the other levels window trickle vents can be integrated in the new windows in the back facade. Mechanical extraction of exhaust air in the 'wet' rooms is through a dedicated ventilation shaft in the bathrooms. Air flows from the supply rooms to the exhaust rooms through the slits under interior doors or through new ventilation vents. A Central+ control system is implemented to assess the

thoroughly integration of information of the heating system, ventilation system and other state sensors (e.g. window opening) in this configuration.

Advantages

The thermal comfort will be high due to the evenly distributed heat through the underfloor heating and cooling. Regarding the ventilation system setup, the impact of ducting is limited: there is no ducting needed for the supply of fresh air, only for exhaust air.

Limitation

Underfloor heating is used in wooden floors, which have a low thermal mass limiting the full potential of surface heating somewhat. The slower heating system, although quicker than conventional embedded surface heating, could make it more difficult to control 'in time' and use sufficient strategies. The mechanical exhaust ventilation causes risks of draught and noise pollution and makes it impossible to recover heat from the exhaust air.

Shortlist

	Technical solution (from longlist)
Heating (and cooling) emission system	Use existing radiators
	New LT radiators
	Typical radiant surface system
	Thin dry radiant surface system
Hybrid heating (and cooling) concepts	Thin dry radiant surface system + use existing radiators
Ventilation concepts	Nominal mechanical ventilation with heat recovery (MVHR)
	Nominal mechanical exhaust ventilation (MEV)
	Central hall-based
	Cascade mechanical ventilation with heat recovery
Ventilation components	Facade integrated ventilation ducts
	Roller shutter ventilation
Controls	1-zone
	Zonal
	Central
	Central+

Table 7 Shortlisted solutions and scenarios for modest house in Belgium

5.2.5. Multi-family townhouse

Only one HVAC configuration for the multi-family townhouse is included in this shortlist. This archetype is the least prevalent in our region and the system configuration researched for the middle-class townhouse could also be applicable to this archetype since they are very similar. The described HVAC concept here below is an ambitious one, with the goal of lowering the water supply temperature for space heating as much as possible (and consequently also lowering the energy demand). The system consists of a cascade mechanical ventilation system with heat recovery on each level of the building. The space heating is provided by a hybrid system with surface radiant heating and the existing radiators.

System Configuration

The floor finishing on each level is removed to place insulation for a good thermal zoning. In the same movement, an underfloor heating joist system is placed on each floor to provide for a base level of heating on a low supply water temperature. The existing radiators are preserved and used to provide the necessary extra heating power when needed (again on a low supply water temperature). The existing shafts in this type of building can serve as a technical shaft for the water pipes of the space heating system and domestic hot water.

The ventilation system is a cascade mechanical ventilation system with heat recovery on each level of the building. Instead of providing fresh supply air in all the dry rooms and exhaust in all the wet rooms, the setup is altered. Fresh air is supplied through the chimneys in the living rooms, which are expected to be in the front of the building. The exhaust air is extracted in the annex through the chimneys again, where a bedroom or bathroom is expected. This setup is possible because bedrooms and living rooms have different times of use.

A simple 1-zone control strategy is implemented in each appartement. The ventilation system is controlled by a single CO_2-sensor in the living room and the space heating by a thermostat in the same room. Thermostatic valves in each room provide further refinement on room-level.

Advantages

The thermal comfort will be high due to the evenly distributed heat through the underfloor heating. The combination of a slow and more quick-responding system will aid in fine control strategies. A limited amount of ducting and intrusions is needed, only ducts in chimneys are required. The total ventilation supply airflow rate is lower, saving on ventilation energy losses. This would make re-using the radiators and implementing a radiant surface system on low water supply temperatures more feasible.

Limitation

The wooden flooring needs to be removed where floor heating is placed which poses a risk of damaging the flooring. The ventilation system is not yet included in the Belgian standards.

5.3. Norway

5.3.1. Climatic and environmental conditions

The climate in Trondheim is defined as Dfc. Subarctic (severe winter, no dry season, cool summer). The climate is characterized by relatively cold winters and relative cool summers. While average temperatures during the cold season are not below -10°C, the occurrence of extreme low minimum temperatures around -15- -20 °C necessitates careful consideration of thermal insulation and high-performance windows, air tightness and energy efficiency to mitigate heat loss. Consequently, heating demands are substantial in this region.

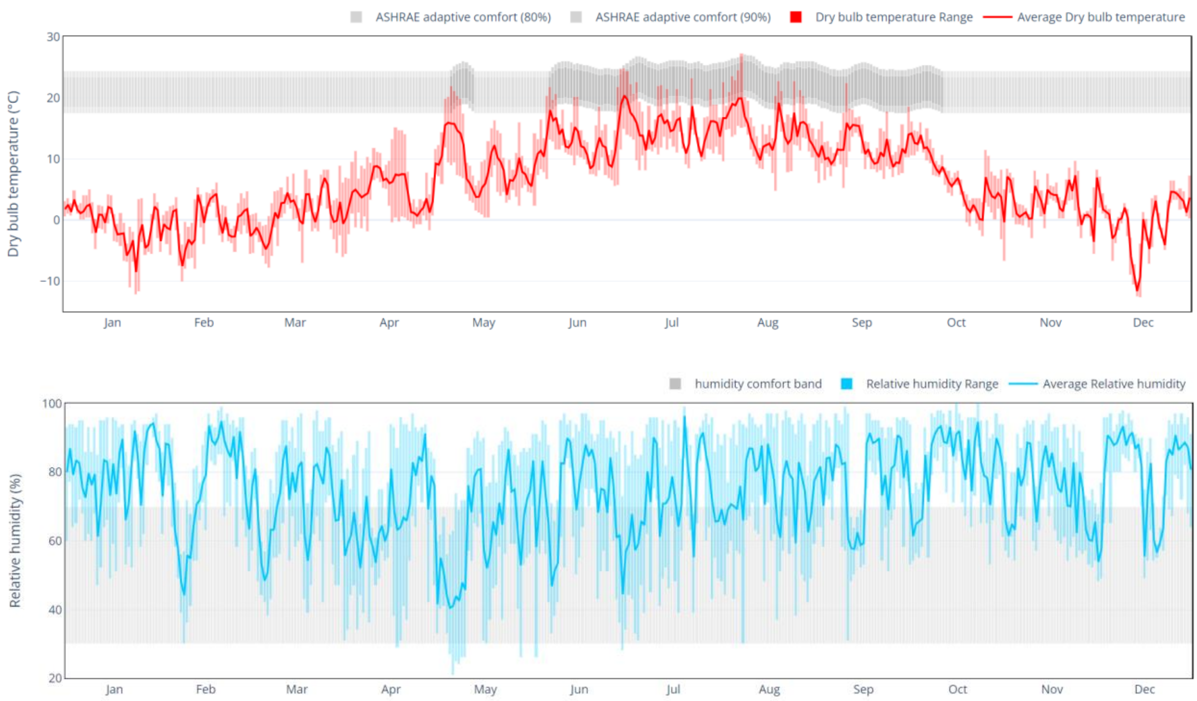


Figure 3 Average dry bulb temperature (top) and relative humidity (bottom) of Trondheim (source: https://clima.cbe.berkeley.edu/).

5.3.2. Wooden houses in Bakklandet

The archetype for residential buildings in Norway primarily consists of wooden houses, resembling those in the Bakklandet neighbourhood. However, unlike Bakklandet, which is subject to significant restrictions due to its historical character and challenging geotechnical conditions, these archetypes don't need to be equally constrained.

Typically, these buildings are two levels high, with some incorporating an additional half-floor in the basement. They are often divided into 2 to 3 apartments and are connected to either a front or a backyard. The wooden elements in these structures are arranged in either vertical or horizontal configurations, creating a distinct architectural style reflective of traditional Norwegian construction practices. Internally, the wood used for cladding and parquet flooring is usually of high quality. Heating systems in these buildings typically rely on electricity due to their inherent compatibility with the wooden structures and as an easy replacement for wood stoves.

In the proposals presented below, solutions that minimise intervention in both the wooden structures and the plumbing systems are prioritised. Hydraulic heating systems, which require significant renovations for installing ductwork and plumbing, pose considerable challenges for these buildings.

Ventilation in these archetypes is predominantly natural ventilation. Installing mechanical ventilation with heat recovery (MVHR) in the heritage buildings of Bakklandet is not straightforward. One of the main challenges is integrating these systems into buildings designed for natural ventilation without disrupting their architectural integrity. The installation of ductwork for MVHR can be particularly problematic in these wooden structures, as it often requires invasive modifications that risk compromising historical elements, such as decorative woodwork, ceiling beams, or other original features. Space constraints within the walls or ceilings of these older buildings with limited height also limit the feasibility of accommodating large ventilation units or ducting systems. Additionally, the outdoor placement of components, such as vents or heat pump units, may require approval from Byantikvaren (Cultural heritage administration), especially for listed buildings in Categories A, B, or C. Despite these challenges, such systems offer significant advantages. MVHR can greatly improve indoor air quality by ensuring a steady supply of filtered outdoor air while recovering heat from the exhaust air, thus reducing overall heating demands. This is particularly beneficial in Trondheim’s cold climate, where natural ventilation can lead to considerable heat loss or thermal discomfort. These systems also help mitigate issues related to poor outdoor air quality during winter, as they can filter incoming air to reduce particulate matter from wood stoves and other pollutants.

Installing wall fans with heat recovery also comes with specific disadvantages. Noise generation is a common issue, as these fans can produce noticeable sounds during operation, which may disrupt the occupants' comfort. This is particularly important in heritage buildings, where the sound insulation of walls may be insufficient to dampen noise effectively. Furthermore, the impact of these fans on airflow distribution within the building must be carefully assessed. In older buildings with compartmentalised layouts and limited open floor plans, in addition to the inherent alternation of the flow, achieving uniform airflow can be difficult, potentially leading to uneven ventilation and temperature distribution.

Heating in these archetypes is often provided via wood stoves, which promote relatively open layouts in most rooms, except for bedrooms where Norwegians traditionally prefer lower temperatures and often no heating. This preference suggests that solutions leveraging airborne heat distribution, such as air-to-air heat pumps, could be suitable.

To achieve higher energy efficiency, in normal practice, renovation strategies would first focus on improving the building envelope through air tightening and enhanced insulation, door and windows, as detailed in WP2. Subsequently, wood stoves are normally being removed and mechanical ventilation installed. Renovation using electricity as heat source either via direct electric heaters or heat pumps is normally the preferred production solution.

5.3.3. HVAC-concept selection

Low-Impact Solutions

Low-impact solutions focus on optimising existing heating systems rather than replacing them entirely. These strategies are particularly relevant for buildings with wood stoves, electric heaters, or district heating systems, where only targeted upgrades are implemented. In buildings with wood stoves, a simple yet effective measure is replacing the existing stove with a modern, energy-efficient model. This upgrade maintains the system's functionality

while reducing emissions and improving overall energy efficiency. Similarly, in buildings equipped with electric heaters, these systems can be retained without significant changes, minimising both cost and structural impact.
For buildings utilising district heating, maintaining the existing system is often the most practical and cost-effective approach. In Trondheim, district heating primarily relies on waste-to-energy plants, which are considered a low-CO_2-intensity heat source. This makes the retention of district heating a sustainable choice, particularly when the system is already integrated into the building's infrastructure.
For buildings in cold climates relying on natural ventilation, low-budget upgrades can entail installing trickle vents in windows to ensure minimum outdoor air flow rates without excessive thermal loss. Motorised windows provide automated ventilation, adjusting based on indoor and outdoor conditions to maintain comfort and efficiency. But this requires a larger budget and will have a higher impact. Upgrading exhaust points with grilles or louvers facilitates better air extraction while preventing draft. If the building design permits, enhancing stack ventilation by ensuring clear and well-insulated vertical air channels for natural convection-driven airflow can be a solution. In addition, most of these buildings already have extraction in the kitchen and bathrooms. Additionally, programmable timers or manual switches can control ventilation openings during peak occupancy while preserving energy during unoccupied periods. Another challenge is the outdoor air quality during winter. Many residents use wood stoves for heating, leading to increased particulate matter in the air, especially during temperature inversions.

<u>Advantages</u>
Using new wood stoves reduce emissions in the heated volume yielding higher indoor air quality and higher energy efficiency. This system replacement has also a lower investment cost compared to complete system replacements.
Regarding changes of electric heaters minimizes costs and structural impact while enabling more advanced control of the system.
Regarding district heating, maintaining existing infrastructure avoids high replacement costs and in places like Trondheim the solution has low carbon intensity.
Regarding ventilation, low-budget upgrades like trickle vents and programmable timers enhance efficiency without significant investment while ensuring a constant minimum airflow rate. Enhancements like motorized windows and upgraded exhaust points improve air extraction and indoor air quality.

<u>Limitation</u>
Investment costs: Upgrading to modern models of wood stoves and automated ventilation systems require an initial investment.
Weather dependency: Effectiveness and thermal (dis)comfort of natural ventilation can vary with outdoor conditions, especially in cold climates.
Air Quality Challenges: Increased particulate matter from wood stoves during temperature inversions can affect outdoor air quality and this together with reduced ventilation rates can affect indoor air quality.

Medium-budget/Impact Solutions
Medium-impact renovations involve transitioning from wood stoves or electric heaters to air-to-air heat pumps, or from district heating systems with radiators to water-based or ground-to-water heat pumps using the same distribution and emission systems. These

changes typically require modifications to both the interior and exterior of buildings, though they are less invasive compared to high-impact renovations as no new distribution system is required. When replacing wood stoves or electric heaters with heat pumps, the primary alterations include installing indoor and outdoor units. Additionally, to address areas like bathrooms that lack sufficient heating from air-to-air systems and often have the door closed, supplemental electric floor heating is often added. This approach minimises disruption while improving energy efficiency and comfort. For buildings with existing radiator-based district heating, transitioning to water-based or ground-to-water heat pumps entails adapting the system to lower distribution temperatures. This requires evaluating radiator performance under reduced temperatures and potentially upgrading or adding radiators to maintain thermal comfort. In Norwegian contexts, such renovations are particularly relevant due to the prevalence of high-temperature district heating systems, such as those in Trondheim. These renovations may also involve addressing changes in heat loss through the building envelope and ventilation systems to ensure efficiency (Alonso, 2018https://doi.org/10.1007/978-3-030-00662-4_26). Implementing ventilation systems, where ventilation units (such as Flexit's Nordic CL2 or the one reported in the section 3.2 of the longlist) are placed in the basement or attic, offers an efficient solution to improve indoor air quality while minimising structural changes. This setup involves connecting the ventilation units to individual rooms using small ducts, reducing the need for extensive modifications to the building's facade with opening of air intakes.
Innovative solutions, such as motorising windows as the ones suggested in the shortlist of WP2, provide an alternative means of ensuring minimum hygienic air supply rates. These systems rely on dynamic control strategies, leveraging indoor and outdoor sensors to optimise window opening. While effective, such designs require the installation of a larger number of sensors and advanced control systems to maintain functionality and efficiency and the risk of incurring thermal discomfort and low air quality should always be assessed. Motorised windows may be particularly advantageous in buildings with architectural constraints, enabling compliance with air quality standards while maintaining design integrity.

Advantages

Energy Efficiency: Transitioning from high temperature distribution and emission systems can yield improved distribution/emission effectiveness.
Cost reductions: The proposed changes do not require new distribution systems reducing costs.
Improved air quality: Installing low impact ventilation systems or motorize windows allow for dynamic control of ventilation while maintaining air quality and comfort

Limitation

Initial Costs: New heating production systems involves significant initial investment.
Complexity: Transitioning to lower distribution temperatures may require evaluating and upgrading radiators. In addition, motorized windows and dynamic control systems require numerous sensors and advanced controls, adding complexity.
Thermal comfort risks: There is a risk of thermal discomfort and low air quality if not properly managed.

High-Impact Solutions

High-impact renovations include replacing individual radiators or wood stoves with centralised radiator-based heating systems. This requires installing extensive piping networks, and constructing technical shafts, all of which can affect building layouts and usable space.

Key decisions in such renovations involve selecting between floor heating and radiator-based systems. Floor heating, while offering even heat distribution, necessitates more invasive renovations, such as replacing high-quality wood flooring. Renovations to improve heating solutions in Bakklandet' s wooden apartment buildings face several challenges, primarily due to the buildings' lack of airtightness and limited insulation. In many cases, residents are reluctant to add sufficient insulation due to space constraints or a desire to preserve the original structure. Waterborne heating systems are often unfeasible, both because of the flooring solutions and high installation costs. Systems like air-to-water or water-to-water heat pumps, which depend on waterborne distribution, are generally not economically viable in this context. Conversely, radiator-based systems typically involve less disruption, allowing existing flooring to remain intact, although additional measures might be required to integrate piping safely. The choice between these systems often depends on the distribution temperature required, which is directly linked to the heating production solution. In Norway, district heating systems generally operate at higher distribution temperatures, particularly in cities like Trondheim, where systems have been designed around these conditions. However, if heat pumps are adopted as the primary heat source, lower distribution temperatures are necessary, significantly influencing system design and operational efficiency. The feasibility of changing the existing system supplied by high temperature district heating with heat pump solutions will depend on the selected radiator solutions, and the changes in heat losses via building envelop and ventilation (Alonso 2018)

The high impact ventilation solutions involve installation of mechanical ventilation with heat recovery. This solution is seen as of high impact due to the need of the installation of ductwork that often will result in either lowering already not too high ceiling or making casing of the ductwork. Some apartment solution such as Flexits (Nordic CL2 or Nordic S2) are relatively compact. During Heritace project one such solution combined with air cleaners and demand control will be tested in a case study.

Advantages

Energy efficiency: Mechanical ventilation with heat recovery enhances energy efficiency by recovering heat from exhaust air. Also, as the ducting is short and the architectural features of the building would be used, distribution loses are also reduced at low SFP

Comfort: Floor heating provides an even heat distribution at lower temperature with most of the losses being recoverable as heat. Radiators can also be selected low temperature, they are less disruptive and can maintain existing flooring, preserving comfort and aesthetics.

Indoor air quality: Low temperature distribution and emission allows for lower dust burning and combined with controllable airflow rates, this ensures good indoor air quality.

Limitation

Initial costs: Extensive piping networks and technical shafts may require significant investment. In addition, invasive renovations, such as replacing high-quality wood flooring, add to costs.

Structural Impact: Installing centralized systems can affect building layouts and usable space. Mechanical ventilation installation may lower ceilings or require casing, impacting aesthetics.
Feasibility Challenges: Waterborne heating systems are often unfeasible in buildings with limited insulation and high installation costs. Changing the temperature supply but not emission system may add to insufficient installed power. Changes in heat loss through the building envelope and ventilation need to be addressed to maintain efficiency.

Experimental Solution

For Northern countries, ventilation strategies often aim to maintain satisfactory indoor air quality and mitigate moisture and mold growth risks in wooden heritage townhouses. These risks are particularly pronounced during renovations that involve measures such as interior insulation, which can introduce thermal bridges and increase the building envelope's airtightness. While such renovations improve energy efficiency, they also elevate the potential for moisture-related problems and mold growth.
To address this, the HeriTACE project will explore the use of air cleaners as a means of eliminating mold spores and reducing the risk of mold formation without the need for increased outdoor air ventilation rates. This approach aligns with the goals of maintaining occupant wellbeing and minimizing energy consumption associated with ventilation. When combined with demand-controlled ventilation, this solution has the potential to sustain high indoor air quality (IAQ) while requiring less energy.
Currently, this approach is at a low Technology Readiness Level (TRL 2). As part of Task 3.3.1 of the HeriTACE project, its feasibility and performance will be systematically investigated to determine its practicality and effectiveness in real-world applications.
This system is being studied because controlling mold spores can significantly reduce mold risks, especially when combined with moisture sensors installed in the room and integrated into the walls. Furthermore, integrating it with demand-controlled ventilation (DCV) based on CO_2, particulate matter (PM), and temperature can enhance overall air quality. Air cleaners effectively remove mold spores, while DCV minimizes other indoor pollutants, ensuring good indoor air quality (IAQ) in an energy-efficient manner.
However, the system's primary disadvantage is its low Technology Readiness Level (TRL), meaning its efficiency and practicality have yet to be fully demonstrated. Additionally, the combined use of DCV and air cleaners could increase costs, adding to the complexity of implementation.

Shortlist

	Production system			distribution			emission		
Existing	Low B/I	Medium B/I	High B/I	Low B/I	Medium B/I	High B/I	Low B/I	Medium B/I	High B/I
Wood stove	New wood stove	A-A HP+ el heater bathroom	A-W/W-W/G-W HP	airborne	Airborne,	waterborne	stove		Radiator/floor heating
Electric heater	Keep El-Heater	A-A HP+ el heater bathroom	A-W/W-W/G-W HP	Point source	airborne	waterborne	radiator		Floor heating
District heating (other places than Bakklandet	Keep DH	W-W/G-W HP		waterborne	waterborne	waterborne	radiator	radiator	Floor heating

Table 8 Shortlisted solutions and scenarios for wooden houses in Bakklandet.

5.4. Estonia

5.4.1. Climatic and environmental conditions

Estonia is defined as Dfb climatic zone (cold, no dry season, warm summer), while being situated in the northern part of temperate climate zone and in transition zone between maritime and continental climate. The yearly average temperature (see Figure 4, top) is ca 6 C, while monthly means in winter reach as low as ca -12 C. Heating degree days ($S_{17°C}$) reach to ca 4200 degree days on average, emphasizing the need for efficient building envelope and heating systems. As the windows of the heritage buildings tend to be rather small and the monthly mean temperatures in summer are below 20°C, cooling has not been the most pressing issue, although heat waves can cause discomfort and climate change has caused increase in summer temperatures recently.

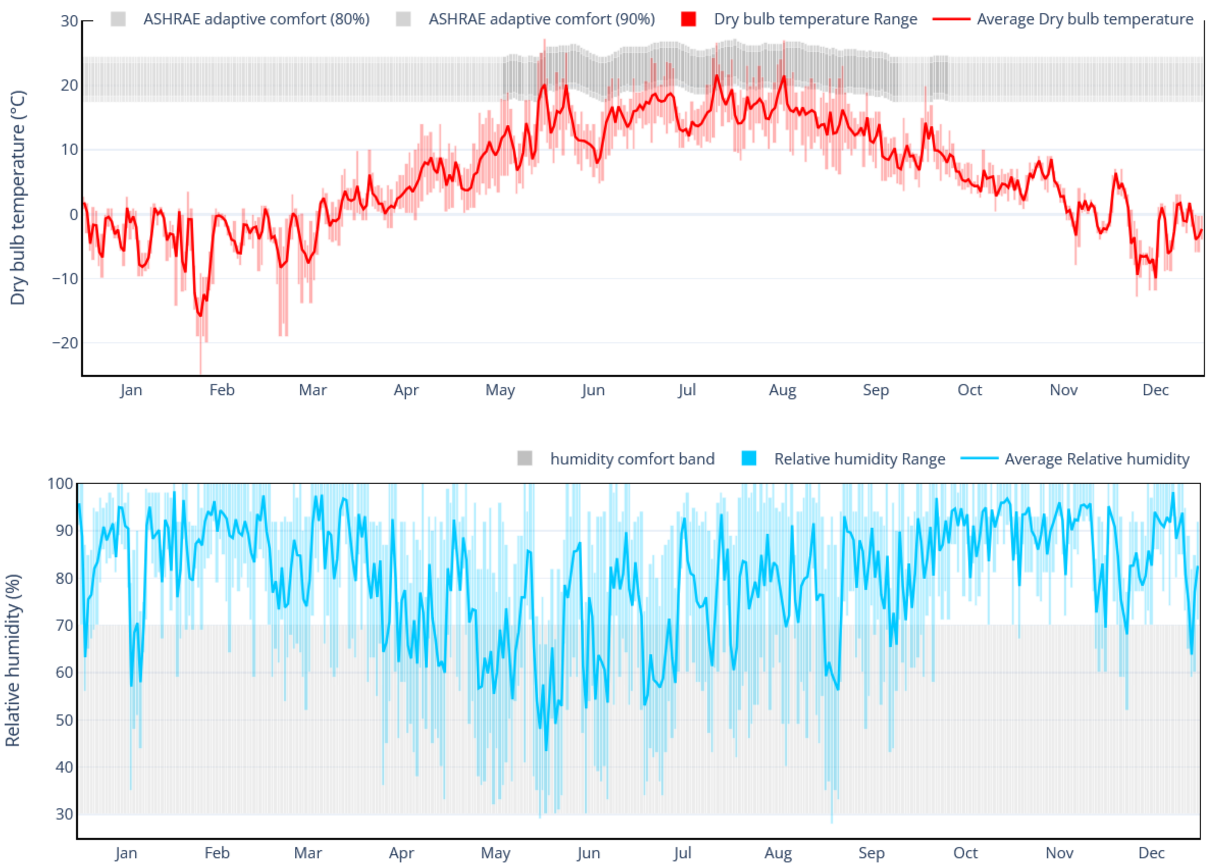


Figure 4 Average dry bulb temperature (top) and relative humidity (bottom) of Tallinn (source: https://clima.cbe.berkeley.edu/).

5.4.2. Wooden apartment building

Wooden apartment buildings typically feature a simple floor plan with a central staircase. The staircase material varies, being constructed of brick in some buildings and wood in others. Most of these buildings have a basement level, except in some cases where the ground floor is directly built on the ground. This straightforward design reflects the practical and functional approach commonly used in the construction of wooden apartment houses.

Wooden houses in the case-study originally used wood-burning stoves as their primary heating system. Heating in these buildings is primarily apartment-specific, with some apartments still relying on wood-burning stoves, while others have been upgraded to radiator systems powered by electricity, gas boilers, or, in one case, district heating. Additionally, most of the buildings feature electric boilers for heating domestic hot water.

The ventilation systems in these buildings rely on natural passive stack ventilation. Air exits through chimneys, and fresh air enters through the building envelope. Consequently, the air exchange rate is influenced by the airtightness of the structures, as most buildings lack modern fresh air valves, leading to ventilation characteristics determined by the building's construction.

The reconstruction of heating and ventilation systems in wooden apartment buildings must address the preservation of their historic character while meeting modern energy efficiency and indoor climate standards. A tailored approach ensures that the upgrades respect the buildings' architectural heritage and materials, maintaining their structural and aesthetic integrity.

Upgrading apartment-specific heating systems involves replacing outdated wood-burning stoves with modern, efficient solutions such as heat pump systems or systems connected to district heating networks. Heat pump systems, including air-to-water or ground-source heat pumps, provide sustainable and energy-efficient heating options, while district heating ensures a reliable and centralised heat supply. In buildings of significant heritage value, operational wood stoves can be retained as supplementary heating options to preserve historical authenticity. These modern heating approaches minimise environmental impact and improve energy efficiency while ensuring a balance between contemporary heating needs and the preservation of the building's historic character.

Considering the climatic conditions and commonly established practices, wooden apartment buildings can adopt one of the following ventilation solutions: an apartment-specific mechanical ventilation system with heat recovery, a building-based mechanical ventilation system with heat recovery, or a floor-specific ventilation system with heat recovery.

For an apartment-specific system, each apartment is equipped with its own ventilation unit, typically installed in a bathroom or kitchen. Supply air is distributed to clean zones such as living rooms and bedrooms, while exhaust air is removed from wet zones like bathrooms, toilets, and kitchens. The main advantage of this solution is its flexibility, allowing for demand-based regulation tailored to individual apartments. However, the system requires more space within the apartment to accommodate the unit and associated ducts for fresh air intake, exhaust air, supply air and extraction air.

In contrast, a building-specific system uses a single ventilation unit to serve the entire building, which can be installed in the attic or, if available, in the basement. This centralised approach reduces the space requirements within apartments.

Alternatively, a floor-specific system can be implemented, where the lower floors are serviced by a ventilation unit located in the basement, and the upper floors by a unit located in the attic. This solution is particularly suitable for multi-story wooden apartment buildings.

The primary advantage of building-specific or floor-specific systems is the reduced space requirement in individual apartments, making them more practical in buildings where space is at a premium. However, these systems are generally less flexible in terms of demand-based control compared to apartment-specific solutions.

Each of these solutions offers distinct benefits and challenges, and the choice should be guided by the building's layout, available space, and the specific needs of its occupants.

Considering the existing heating and ventilation solutions in wooden apartment buildings, any modifications and upgrades made during reconstruction must be assessed for their impact on different parts of the building, considering the architectural values of the buildings. For the buildings studied, the primary value lies in their exterior appearance, which allows for more flexibility in implementing heating and ventilation system upgrades within the interior of the buildings. Limitations are primarily technical or spatial in nature.
The exterior appearance is most affected by the ventilation system. In terms of heating systems, an air-to-water heat pump solution may impact the exterior, as it requires finding an appropriate location outside the building for the heat pump's external unit. This must be done carefully to preserve the building's visual integrity and architectural value.

5.4.3. Stalinist style brick apartment

When addressing the reconstruction of heating and ventilation systems in stone-structure buildings located in heritage areas, it is essential to consider the unique characteristics of these buildings, including their historical value and construction features. The goal is to balance energy efficiency with the preservation of architectural heritage. The size of the building also plays a significant role in determining suitable solutions. Smaller buildings, with two to three floors, often allow for simpler system designs compared to larger buildings with up to five floors, which may require more complex approaches.
Building-specific heating systems, such as district heating or heat pump systems, are often preferred in stone-structure buildings. District heating is well-suited for urban areas where connection to the network is feasible. Heat pumps, such as air-to-water or ground-source systems, provide sustainable and energy-efficient heating options tailored to the building's needs.
Centralised heating systems typically involve placing equipment like boilers in the basement, distributing heat through radiators or underfloor heating. This approach minimises the need for individual heating equipment in each apartment, preserving interior spaces.
Although less common in heritage buildings, apartment-specific systems can be used in special cases where each unit requires independent energy sources. However, these solutions are generally less efficient and may disrupt the building's historic appearance.
In smaller buildings with two to three floors, heating solutions are often simpler to implement due to shorter distribution distances and reduced system complexity. In larger buildings with up to five floors, centralised systems must accommodate greater demands and ensure even distribution, which can increase the complexity of the design and installation.
A mechanical supply and exhaust ventilation system with heat recovery is the most suitable solution for stone-structure buildings. The ventilation unit can be placed in the attic or basement, providing centralized control for the entire building.
This solution reduces the need for ductwork and equipment within apartments, optimising space usage, an important consideration in heritage buildings where interior preservation is a priority.
Floor-specific ventilation systems can serve as an alternative, especially in multi-story buildings. For example, lower floors can be serviced by a unit located in the basement, while upper floors are serviced by a unit located in the attic.
If apartment-specific mechanical ventilation is used, the unit must be installed in technical spaces within each apartment, such as bathrooms or kitchens. Supply air is distributed to living spaces, while exhaust air is extracted from wet areas like bathrooms, toilets, and

kitchens. While this approach allows for more flexible demand-based regulation, it requires additional space in each apartment to accommodate the unit and associated ducts for air intake, exhaust, supply, and extraction.

Smaller buildings with two to three floors provide greater flexibility for ventilation system design, as shorter duct runs and fewer apartments simplify installation. Larger buildings with four to five floors often require more advanced solutions, such as floor-specific systems, to ensure effective airflow distribution and system efficiency.

All solutions must be planned in collaboration with heritage area rules. Equipment, ductwork, and ventilation networks should be visually discreet and harmoniously integrated into the building's historical context. For example, air intake and exhaust ducts can be concealed or designed to match the building's facade.

For stone-structured buildings in heritage areas, the size of the building significantly influences the complexity of heating and ventilation solutions. Smaller buildings with two to three floors allow for simpler system designs, while larger buildings with up to five floors may require more intricate approaches, such as floor-specific systems. Preferred heating systems include district heating and heat pumps, while ventilation should rely on mechanical supply and exhaust systems with heat recovery. These solutions ensure comfort and energy efficiency without compromising the architectural identity of the building.

5.4.4. HVAC concept selection

In Estonian cities and larger settlements, district heating networks have a fairly extensive coverage. As a result, during building renovations and heating system upgrades, the guidelines often recommend connecting to district heating, providing an environmentally friendly and efficient solution for heat supply. District heating allows buildings to utilise a centralised heat source, reducing the need for individual heating systems and conserving resources while preserving the exterior appearance and architectural integrity of the buildings (Volkova, A., Krupenski, I., Kovtunova, N., Hlebnikov, A., Mašatin, V., & Ledvanov, A. (2023)).

Considering Estonia's climatic conditions, the guidelines for ventilation reconstruction prioritise mechanical supply and exhaust ventilation systems with heat recovery. This solution ensures optimal indoor air quality through adequate air exchange while maintaining thermal comfort with minimal energy consumption. A heat recovery system significantly reduces heat loss, providing an efficient and environmentally friendly ventilation solution (Mikola, A. (2022)).

Based on building archetypes, the solution concepts can be categorised as followed:

Low-Impact Solutions

If the building already utilises a radiator-based heating system, the low-impact approach involves maintaining the existing radiator network while replacing the current heat source with a more efficient one, such as connecting to district heating.

A low-impact ventilation solution ensures the minimum required air exchange by utilising existing flues, enhanced with controllable exhaust fans. Fresh air is compensated through minimal interventions, preserving both the building's structure and exterior appearance.

Medium-Impact Solutions

Converting apartment-specific radiator heating systems into a centralised building-wide heating system. This requires the installation of risers or main pipes to connect apartments to a central heating unit, necessitating additional technical shafts and moderate adjustments to the interior.

Implementing a floor-specific ventilation system where ventilation units are placed in the basement or attic. Connections to apartments are established through existing flues and limited new ducts, minimising the number of air intake and exhaust openings on the building's exterior.

High-Impact Solutions

Installing a completely new heating system, such as replacing stoves with a new radiator-based heating network. This involves extensive interior modifications, including the installation of piping and technical shafts, significantly affecting the layout and usable space. Ventilation solutions involve multiple air intake and exhaust openings on the facade or roof, particularly in apartment-specific ventilation systems where each unit requires individual connections. This approach has the most noticeable impact on the building's exterior appearance.

This categorisation allows for the assessment of potential solutions based on their compatibility with building archetypes, architectural values, and technical feasibility.

Shortlist

	BAU	HER	ECO
Ventilation			
Existing	x	x	
Nominal mechanical exhaust ventilation	x	x	
Nominal mechanical ventilation with heat recovery (apartment specific)			x
Nominal mechanical ventilation with heat recovery (building specific)			x
Cascade mechanical ventilation with heat recovery			x
Heat source			
Existing	x	x	
Wood burning stove (new)	x	x	
Air to Air heat pump	x	x	x
Air to Water heat pump			x
Ground Source heat pump			x
District Heating			x
Distribution			
Existing Radiators	x		x
Existing wood burning stove	x	x	
Wood burning stove (new)	x		x
Air to Air heat pump	x		
Radiators (new)		x	x
Floor heating (new)		x	x
Skirting heating		x	x
Control			
1-zone	x	x	x
Zonal	x	x	x
Central		x	x
Central +			x
Model Predictive Controls			x

Table 9 Shortlisted solutions and scenarios for wooden and Stalinist brick apartment building archetypes.

For different energy saving level, the packages can be combined considering the current renovation practice (BAU), packages that alter the architectural appearance the least to save heritage buildings (HER) and packages with the best economic effect (ECO). These three can be seen as representative of the different attitudes of different building owners.

Bibliography

Alonso, M. J., & Sartori, I. (2018). What is the minimum district heating supply temperature in residential buildings in Norway?. In *Cold Climate HVAC Conference* (pp. 303-316). Cham: Springer International Publishing. https://link.springer.com/chapter/10.1007/978-3-030-00662-4_26

Caillou, S., Pecceu, S., & Van Gaever, R. (2023). Innovatieve ventilatiesystemen voor woningen in een renovatiecontext. (Innovation Paper 41; p. 88). Buildwise. https://www.buildwise.be/nl/publicaties/innovation-papers/41/

Koninklijk Meteorologisch Instituut. (n.d.). Het Belgisch klimaat. KMI. Retrieved 5 November 2024, from https://www.meteo.be/nl/klimaat/klimaat-van-belgie/het-belgische-klimaat-maand-na-maand/algemeen

Maiheu, B., Van den Berghe, K., Boelens, L., De Ridder, K., & Lauwaet, D. (2013). Opmaak van een hittekaart en analyse van het stedelijk hitte-eiland effect voor Gent (RMA/N78H7/2012-0003). https://www.ugent.be/ea/civil-engineering/amrp/nl/onderzoek/toegepast-onderzoek/hittekaart-gent-eindrapport2013.pdf

Mikola, A. (2022). Ventilation Performance in Deep Renovation of Multifamily Apartment Buildings [PhD thesis, Tallinn University of Technology]. https://digikogu.taltech.ee/et/item/55e3f98e-1a11-498e-98c5-3068a231e2d5

Millison, A. (2019). Appendix C: Koppen Geiger Classification Descriptions. In Permaculture Design: Tools for Climate Resilience. Oregon State University. https://open.oregonstate.education/permaculturedesign/

Volkova, A., Krupenski, I., Kovtunova, N., Hlebnikov, A., Mašatin, V., & Ledvanov, A. (2023). Converting Tallinn’s historic centre’s (Old Town) heating system to a district heating system. Energy, 275, 127429. https://doi.org/10.1016/j.energy.2023.127429