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Repository of Deep Renovation Packages Based on Industrialized Solutions: Definition and Application

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Abstract: Renovation Wave aims to boost the uptake of deep renovation towards the CO_2 emission targets for 2030. In this perspective, there is the need of technologies and solution sets for improving the deep renovation process as well as demonstrating the performances for supporting the stakeholders in the decision-making process. To cope with the issue, this work presents a methodology for setting up a repository of building deep renovation packages that integrates industrialised facade technologies and more traditional solutions. The performances feeding into the repository have been evaluated by means of transient detailed simulations on a set of reference buildings in representative European climate conditions. The renovation packages are evaluated in terms of key performance indicators dealing with five areas: energy, comfort, pollutant emissions, cost, and renovation time. The defined repository includes 289 assessed technology packages and associated performances across Europe, providing a comprehensive support to identify the most effective solutions according to the user needs. The paper presents the application of the repository with two examples of stakeholders' decision-making paths for selecting the deep renovation packages according to different priorities and expected targets.

Keywords: deep renovation; energy performance assessment; decision support

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1. Introduction

Although it has been estimated that around 75% of the European building stock is inefficient according to the current energy performance requirements, and more than 40% of the buildings was built before 1960 [1], only 1% undergoes energy renovation each year [2]. On the other hand, the European Commission sets the Climate Target Plan 2030 [3], which established a reduction in the EU CO_2 emissions of 55% by 2030 (in comparison to 1990 levels). This means that buildings will be required to reduce their whole energy consumption for heating and cooling of at least of 18% in order to reach the 2030 target [2].

To meet this target, effective methods for industrializing the renovation process and viable financial schemes are needed to optimize the investment, while reducing the construction site impact. For enabling that path towards the target, at the end of 2020 the European Commission launched the Renovation Wave, aimed to tackle the main challenges that are currently undermining the uptake of energy renovation across Europe. Another objective is to foster the implementation of building deep renovation, namely a series of interventions leading to at least a 60% energy saving, which currently involves on average 0.2% of the EU building stock each year [2]. Although the advantages of deep renovation have been demonstrated [4,5], the current practice usually deals with minor and single interventions (e.g., wall or roof insulation, window replacement, installation of new boilers or heat pumps, integration of a photovoltaic system, etc.) that are implemented without an overall coordination and organic vision of the whole building performance including a reduction in CO_2 emissions and renewable sources exploitation [6]. The reason is that there are still many barriers to address that involve technical, financial, and social aspects of deep renovation [7,8]. Among these the complexity of implementing a deep renovation, the high investment cost and the lack of motivation of the final users represent the main obstacles [9].

In recent years, several research projects financed by the Horizon 2020 Programme of the European Commission aimed to address the abovementioned barriers through the development of industrialised technology solution sets, the assessment and demonstration of their performances through exemplary case studies and prototypes, as well as viable financial models enabling the replication [10–16].

The application of industrialised renovation has been largely investigated in the literature, focusing on envelope elements [17–20], HVAC components [21] and technologies for harvesting renewable sources [22]. The performances of these technologies are usually evaluated through both laboratory tests [23] and on-site monitoring at the scale of single buildings or prototypal components [24,25]. Nonetheless, these studies aim at the development of a single technology, and do not provide an organic assessment of the potential benefits of existing buildings at larger scale, considering different climatic contexts and user needs.

A wider evaluation of the positive impact on the building stock is essential for supporting building renovation uptake across Europe, since it allows quantifying the potential savings and benefits and to prioritize the most effective interventions for the user purposes [26]. In this regard, there are several studies that deal with renovation scenarios at building stock scale through different approaches: the application of statistical methods [27], the definition of a reference database of solutions and associated performances [28] or, in most cases, by defining a set of building archetypes [29–31].

Nevertheless, these studies focused on the assessment of the potential energy saving coupled with the economic viability of the interventions, considered as main strategic issues in the prioritization of the interventions while the comfort conditions and the potential duration of the construction sites have not been considered. Although cost optimality is an essential requirement for a renovation [32], it has been largely demonstrated that comfort perception is crucial both before renovation, for motivating the users in implementing a deep renovation [33], and after the interventions, for ensuring that the foreseen energy saving does not compromise the efficient operation of the renovated building [34–36]. Moreover, another parameter usually neglected in the current practice is the evaluation of the construction site duration associated to different technical solutions. It represents useful information for the stakeholders of the renovation, since the works' inconveniences can mean long-lasting impact on occupant well-being, and this knowledge may significantly support the decision-making process, especially in the case of industrialised technologies.

The evaluation of industrialised solutions requires innovative approaches that enable a comprehensive performance assessment with the support of a structured parametrization of the renovation packages. As far as identified by the literature review, there is the need to define a structured and systematic approach for comparing the overall performances of deep renovation solutions for residential buildings across Europe which still needs to be addressed.

Therefore, to cope with these challenges, this work aims to define a structured repository of deep renovation packages tailored to the specific needs of the European residential building stock. The repository is defined by using the archetype approach, with a focus on target countries representing the main specificities of one of the defined European geoclusters (i.e., homogeneous region across Europe). It contains a comprehensive list of indicators, assessed through a detailed simulation-based performance analysis that present the results of 289 renovation packages across Europe, for an overall amount of 3468 variants. The indicators deal with energy, economic, environmental aspects as well as the comfort conditions of the occupants and the complexity of the construction sites. The evaluation of such solutions requires innovative approaches that enable a comprehensive performance assessment with the support of a structured parametrization of the renovation packages (RPs) by means of hourly detailed simulations and estimation of cost as well as renovation time.

This paper presents the methodology adopted for structuring and populating the repository of deep renovation packages, the selected performance indicators and the approach for their assessment. Finally, a potential application for the definition of renovation strategies according to the specific needs and to the stakeholder expectations is presented.

2. Methodology for the Development of the Repository

In this research, a set of deep renovation technologies were combined into 289 RPs that were likely to be energy effective in the European context. Then, the deep RPs have been tailored according to the local specificities, that are investigated through the geocluster approach and representative building archetypes, and their performances have been assessed by means of dynamic simulations. The steps of the approach for defining the repository of deep renovation packages are summarised in Figure 1 and described in the following sections.

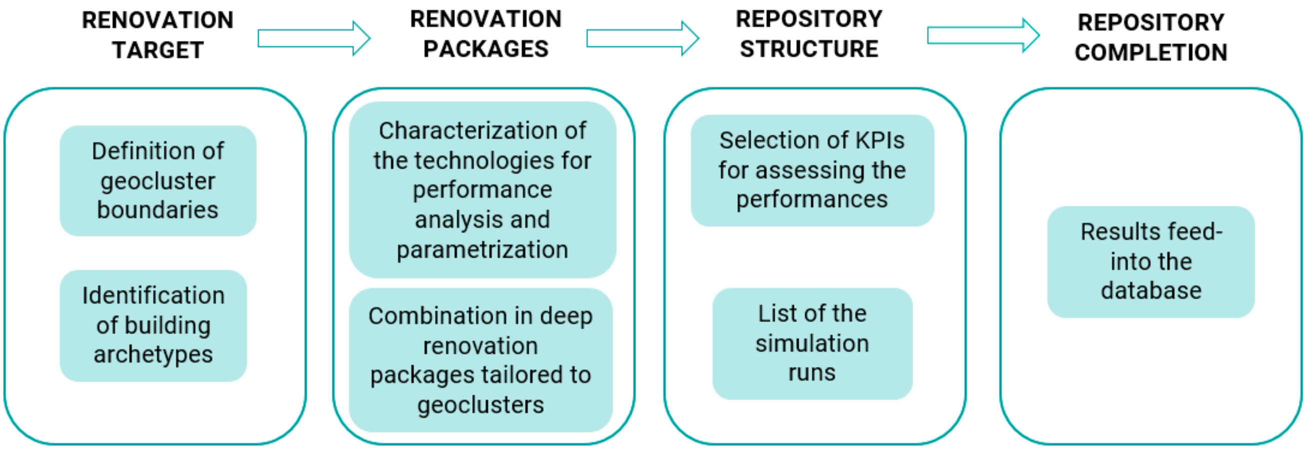


Figure 1. Overview of the methodology for the definition of the repository of deep renovation packages.

2.1. Geocluster and Building Archetypes

To provide a European framework for the parametric performance analysis, Europe has been divided in six geoclusters, identified as homogeneous areas according to a set of identified key parameters. In particular, the division has been defined according to qualitative and quantitative considerations and by comparing the weather conditions, as well as features of the residential building stock (share of single and multi-family houses), the average building performances provided by the law (in terms of U-value for the envelope) in each EU country, according to the information available in the European Building Stock Observatory and the other relevant databases of the European building stock [37,38]. Moreover, the national boundaries have been used since their influence on technical constraints and legislative requirements in case of renovation (Figure 2). For each geocluster the authors have been supported by a local team in reference countries, taking part in the H2020 project 4RinEU [13], that implemented one of the defined approach and renovation packages either on a demo case or within a feasibility study [39].

In particular, the defined geoclusters were:

- Geocluster North: Northern Europe countries with cold climate and prevalence of single-family houses (62% vs. 38% multi-family houses), average U-value for opaque envelope 0.27 W/m^{2}K. Reference country: Norway (Oslo)
- Geocluster N-East: Northern East Europe countries with cold climate and large number of multi-family houses built between 1960 and 1990, with prefabricated concrete panel, average U-value for opaque envelope 0.22 W/m^{2}K. Reference country: Poland (Warsaw)

- Geocluster Cont: Continental West and central with continental climate. The building stock is mainly composed of single-family houses (67%) and there is no prevailing construction period, thus the stock presents different construction features (masonry, concrete or prefabricated structure), average U-value for opaque envelope 0.31 W/m^{2}K. Reference country: The Netherlands (Amsterdam)
- Geocluster East: Continental East, main building typology is single-family with a significant number of multi-family houses built after the 2nd World War with prefabricated concrete structure, average U-value for opaque envelope 0.32 W/m^{2}K. Reference country: Hungary (Budapest)
- Geocluster Med: Mediterranean countries with warmer climate, where the building stock is split almost equally in single and multi-family houses (SFH 52%, MFH 48%) built in different construction periods mainly with masonry or concrete structures, average U-value for opaque envelope 0.85 W/m^{2}K. Reference country: Spain (Barcelona)
- Geocluster Atl: Atlantic zone with cold oceanic climate and single-family houses as main building type (84%), average U-value for opaque envelope 0.27 W/m^{2}K. Reference country: Ireland (Dublin)

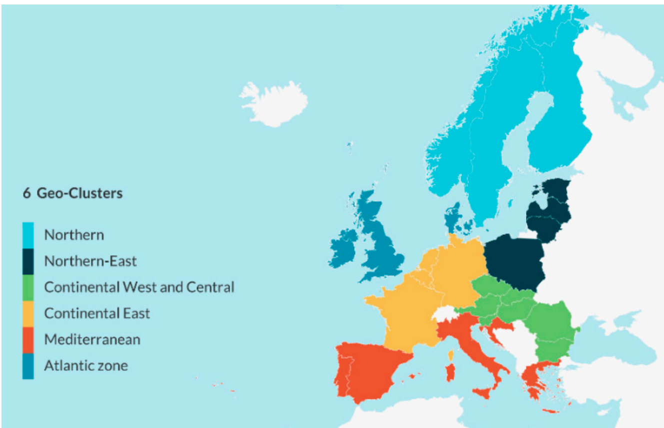


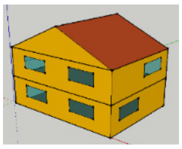
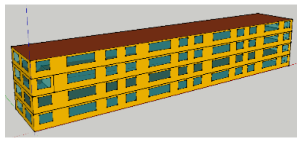
Figure 2. European Geoclusters.

For each geocluster, two representative building archetypes in the respective reference country have been selected through a dedicated building stock analysis: single family and multi-family houses. The source for this selection was the national building typologies developed as part of the Tabula project [40] for the reference countries of the geoclusters. All the archetypes have been selected among these representative buildings, with a focus on the construction period 1950-1980, identified as most relevant for a deep renovation with prefabricated technologies. In fact, on the one hand, the replication potential in that period is considered relevant, since the building façades do not usually present conservation measures [41] and, on the other hand, the energy saving potential is the more relevant [42].

To keep the number of simulation models manageable, the archetypes have been simplified in two main geometries, namely single-family house (SFH) and multifamily house (MFH), that have been used for the simulation in each geocluster (Table 1). The selection was performed by collecting the geometries of SFH and MFH for the selected period and in each reference country, and then the archetypes presenting the median dimension among the ones available from the Tabula database have been chosen for the analysis.

The specific thermal transmittance of existing building envelope elements and HVAC features have been assigned according to the reference country and the adopted construction period (1950–1980).

Table 1. Building geometries.

	Single Family House (SFH)	**Multy-Family House (MFH)**
		
Total Floor Area [m^2]	228	3456
Floor heigh [m]	2.5	2.8
Number of floors [n]	2	4
Shape ratio [-]	0.72	0.37
Window to Wall Ratio [%]	13%	31%
U_{wall} [W/(m^2K)]	MED = 2.55 EAST = 1.63 NORTH = 0.44 CONT = 1.59 ATL = 1.62 N-EAST = 1.55	MED = 1.33 EAST = 1.4 NORTH = 0.57 CONT = 1.64 ATL = 1.59 N-EAST = 1.30
U_{window} [W/(m^2K)]	MED = 5.44 EAST = 2.82 NORTH = 2.82 CONT = 2.82 ATL = 5.16 N-EAST = 5.16	MED = 5.29 EAST = 2.83 NORTH = 2.83 CONT = 2.83 ATL = 5.29 N-EAST = 5.29
U_{roof} [W/(m^2K)]	MED = 4.16 EAST = 1.09 NORTH = 0.23 CONT = 1.55 ATL = 2.30 N-EAST = 0.57	MED = 1.97 EAST = 0.846 NORTH = 0.30 CONT = 1.48 ATL = 1.41 N-EAST = 0.34

2.2. Renovation Packages

A deep renovation is identified as a set of interventions that can bring an existing building to save at least 60% of the primary energy used for its operation [9]. For the purposes of this study, the performance of a series of deep RPs with different efficiency levels and costs have been investigated. The deep RPs have been defined by coupling innovative technologies based on prefabrication, as developed within the H2020 project 4RinEU [13] (focusing on multi-functional façade elements and smart ceiling fans), with traditional solutions for improving the envelope performances, increasing the efficiency of the HVAC system and exploiting renewable energy sources available on site.

Table 2 reports the description of the technologies applied within the renovation packages and the main design parameters affecting the building performances for each geocluster. Further details on the renovation packages and technologies are included in [43] and [44].

The defined deep renovation packages present the integration of functions and technical elements in the prefabricated façade, with the aim of speeding up the installation process and of providing systemic solutions for an effective renovation.

The performances of the deep renovation packages were assessed by means of the software Trnsys [45], used for the definition of hourly dynamic models with detailed simulation of the building, HVAC system, control strategies and energy production from renewable energies. In particular, the configurations of PV and ST systems are tailored for each geocluster according to a detailed optimization based on cost-effectiveness and energy matching between consumption and production on hourly base by applying the approach described in Lovati et al., 2020 [46].

The different combinations between renovation packages have been studied performing a parametric analysis using JEplus tool [47] for the building geometries in the 6 climatic areas identified with the reference countries of the selected geoclusters. The detailed description of the simulation procedure, settings and boundary conditions are reported in [39].

Table 2. Technologies description and affected parameters in each geocluster.

Technology	Description and Affected Parameter	Geocluster 1		Geocluster 2		Geocluster 3		Geocluster 4		Geocluster 5		Geocluster 6	
Traditional Heating System	High-performance condensing boiler. Efficiency of the subsystems: emission (95%), regulation (99%), distribution (99%) and generation (97%)	Heating Power MFH: 36 kW SFH:6 kW (a)		Heating Power MFH: 35.6 kW SFH: 6 kW (a)		Heating Power MFH: 27 kW SFH: 4.5 kW (a)		Heating Power MFH: 31.4 kW SFH: 5.2 kW (a)		Heating Power MFH: 20 kW SFH: 3.3 kW (a)		Heating Power MFH: 24kW SFH: 4 kW (a)	
Heat Pump Heating System	Replacement of the existing boiler with a heat pump.	COP = 3											
Decentralized Ventilaiton Machine	Facade integrated ventilation devices with heat recovery. Power up to 20 W and provided airflow of 42 m^3/h with 70% heat recovery efficiency.	Minimum ventilation rate 1 $m^3/(h\ m^2)$ [48]		Minimum ventilation rate 1.39 $m^3/(h\ m^2)$ [48]		Minimum ventilation rate 3.24 $m^3/(h\ m^2)$ [48]		Minimum ventilation rate 1.51 $m^3/(h\ m^2)$ [48]		Minimum ventilation rate 1.5 $m^3/(h\ m^2)$ [48]		Minimum ventilation rate 1.08 $m^3/(h\ m^2)$ [48]	
Centralized Ventilaiton Machine	Balanced AHU with heat recovery façade integrated. The machine provides 600 m^3/h, with power 140 W, with an 81% heat recovery efficiency.												
PV Integrated	Installation of PV. Each module is 1.44 m^2 with a peak power of 255 W and an efficiency of 16.5%.	Size and distribution of PV panels field to be integrated in building envelope have been optimized on the south façade and on the roof for each geocluster and different building geometries. The optimization has been performed with a tool developed by Eurac and named Early Reno [46]. It considers the yearly irradiation, with hourly time-step, on an available set of panels, and suggests as an output the configuration with the best positioning to have the highest net present value (NPV) within a defined period.											
	Geocluster	Geocluster 1		Geocluster 2		Geocluster 3		Geocluster 4		Geocluster 5		Geocluster 6	
	Bui Type	MFH	SFH	MFH	SFH	MFH	SFH	MFH	SFH	MFH	SFH	MFH	SFH
	PV flat roof [m^2]	70		80		70		70		80		77	
	PV South [m^2]	40	10	50		40		40		63		50	
	PV Roof East [m^2]		36				36		36		36		36
	PV Roof West [m^2]		36		36		36		36		36		36
Smart Ceiling Fan & Cooling System	Installation of smart ceiling fans	The aim of the ceiling fan is to create an air movement able to lower the perceived temperature by the occupants, and hence reducing the energy demand for space cooling. This was modelled with the method proposed by [49], which enables an increase in the set-point temperature up to 28 °C during summer without compromising comfort.											

Table 2. *Cont.*

Technology	Description and Affected Parameter	Geocluster 1	Geocluster 2	Geocluster 3	Geocluster 4	Geocluster 5	Geocluster 6
Retrofit Wall Typology	Two different layouts of timber prefabricated multifunctional façade. The structure is timber framed and insulated with cellulose fiber.	Uwall: 0.2 W/m^{2}K 0.1 W/m^2 K	Uwall: 0.2 W/m^{2}K 0.1 W/m^{2}K	Uwall: 0.2 W/m^{2}K 0.1 W/m^{2}K	Uwall: 0.2 W/m^{2}K 0.1 W/m^{2}K	Uwall: 0.75 W/m^{2}K 0.29 W/m^{2}K	Uwall: 0.2 W/m^{2}K 0.1 W/m^{2}K
Window Typology	Two different new window typologies to be installed in the prefabrication phase within façade modules	• Low-E double-glazing ($U_{glazing}$ = 1.24 W/m^{2}K) Triple glazing filled with Argon ($U_{glazing}$ = 0.61 W/m^{2}K) and High performing frame (U_{frame} = 1 W/m^{2}K)					
Shading System	Advanced shading system control integrated in the Prefabricated Multifunctional Façade (PMF).	Shading on windows has been assumed to be activated considering a shading factor of 80% if three conditions are met: • Global vertical irradiation on the façade element greater than 140 W/m^2 • Room temperature greater than 24 °C (shades removed if <23 °C) • 24 h moving average ambient temperature (previous 24 h) greater than 12 °C					

(a) Limited heating power from calculation considering transmission and ventilation losses; design temperature from 2005 ASHRAE Handbook—Fundamentals.

The definition of the simulation list has been developed by combining all the different variants (i.e., identified by the performances reported in Table 2). In particular, for each building archetype (2), in each geocluster (6), 289 configurations based on the combination of the technologies reported in Table 2 are evaluated in terms of the Key Performance Indicators (KPIs) described in Section 2.3.

2.3. Key Performance Indicators

The performance assessment of the renovation packages includes a series of indicators dealing with five main areas: energy, comfort, emissions, cost, and renovation time. The availability of multicriteria information allows for implementing different decision-making processes, tailored according to the renovation priorities and the specific needs of the stakeholders. The repository of solutions allows supporting the preliminary phase of the design process by providing an overall figure of the achievable performances, for the representative archetypes in each geocluster, and the relation with cost and duration of the construction site.

2.3.1. Energy and Environment

The energy performance of the renovation includes indicators for consumed and produced energy, which have been assessed through a one-year simulation on an hourly base.

The indicators are:

- Net energy demand for heating and cooling ($NE_{H,C}$ [kWh and kWh/m^2]), depending on the envelope performances
- Final energy demand for heating, cooling, lighting, ($FE_{H,C}$ [kWh and kWh/m^2]), by including the efficiency of the systems
- Primary energy demand heating, cooling, ($PE_{H,C}$ [kWh and kWh/m^2]), evaluated by applying the standard factors in the reference countries for each geocluster
- Final energy demand for ventilation (FE_{Vent} [kWh])
- Lighting final energy demand for lighting (FE_{light} [kWh])
- Final Energy demand for smart ceiling fan operation
- PV production (E_{PV} [kWh]): electricity generated by the photovoltaic system installed in the renovation scenario.

Concerning the environment area, the adopted indicator is the amount of CO_2 emissions (in kgCO_2/year) due to the building energy consumption for heating and cooling, defined according to the national CO_2 emission factors according to the renewable energy sources and the used energy vector.

2.3.2. Comfort and Indoor Air Quality

The indicators of this area allow assessing the foreseen improvement of comfort and indoor air quality conditions after the renovation. The evaluation has been performed by adopting the Fanger model [50] for evaluating the comfort condition during the heating period (September–May) and the adaptive model [51,52] for the free-floating and cooling period (June–August) in a sample apartment for the archetypes MFH and SFH. In particular, the assessment focuses on the number of hours in compliance with Cat I and II as defined by the standard ISO 7730 [53] and EN ISO 16,798 [52] that identify, respectively, the high and the normal level of comfort expectations considering both the hygrothermal and indoor air quality conditions. The indicators included in the repository are:

- Occupied hours in Cat. I, Cat. II, Cat. III, Cat IV during heating period according to Fanger model ($\tau_{\text{Fanger, CatI/Cat II/Cat III/Cat IV}}$ [h])
- Occupied hours in Cat. I, Cat. II, Cat. III, Cat IV during cooling period according to adaptive model ($\tau_{\text{Adaptive, CatI/Cat II/Cat III/Cat IV}}$ [h]).

- Overheating Degree: OHD [°C] = $\sum_{t=1}^{8760}(\theta_t - 27)$, if the indoor air temperature in the sample room is higher than 27 °C (θ_t > 27 °C)
- Overheating degree hours: number of hours when $\theta_{op,\ int}$ (internal operative temperature) is higher than 27 °C (ODH_{27} [h])
- Severe overheating degree hours: number of hours when $\theta_{op,\ int}$ is higher than 29 °C (ODH_{29} [h])
- Occupied hours in Cat. I, Cat. II, Cat. III, Cat IV according to CO_2 concentration: considered as percentage of hours when the CO_2 concentration is lower than, respectively, 750 and 900 ppm ($\tau_{CO2,\ CatI/CatII/Cat\ III/Cat\ IV}$ [%])

The charts in Figure 3 show the additional hours in Cat I and II after the renovation for the deep RPs.

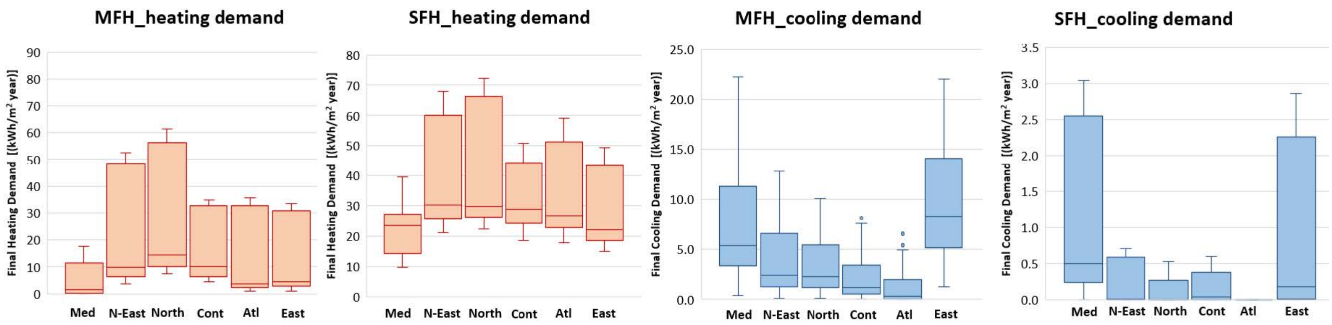


Figure 3. Box-plot charts of heating and cooling final energy demand for multi-family and single-family houses in the six geoclusters.

As established by the standard EN ISO 16798, the indoor air quality is evaluated by estimating the concentration of pollutants (namely, CO_2) in comparison to the outdoor conditions.

2.3.3. Renovation Costs

The repository includes the total investment cost (in € and €/m^2 according to the building surface) for each renovation package, that has been calculated as the sum of:

(I) *Renovation components:* the costs for the integration of different technologies in the package—this amount includes the material or device costs as well as the assembly/integration and installation costs of the technologies that have an impact on the building performances.

(II) *Additional costs*: the costs for the specific user preferences (e.g., finishing materials) and depending on the initial conditions of the building (e.g., structural safety) or general organization of the construction site (e.g., use of scaffolding). These factors do not have a direct impact on the performance of the renovation, but on its aesthetics, costs, and time.

The costs for the envelope have been estimated through the support of a specialised façade manufacturer that identified with the authors the main variables and possible variants for determining a reliable range for renovation. Costs for the other renovation technologies (i.e., HVAC system and renewables) have been deduced from commercial sources, technical sheets and building sector websites and normalised according to the façade surface, considering a reference Window-to-wall ratio according to the features of the defined building archetypes.

Figure 4 reports the minimum and maximum costs with a detailed breakdown for the renovation technologies and additional costs. For the renovation components, the costs are related to different technologies for envelope, HVAC and renewable exploitation as reported in Table 2.

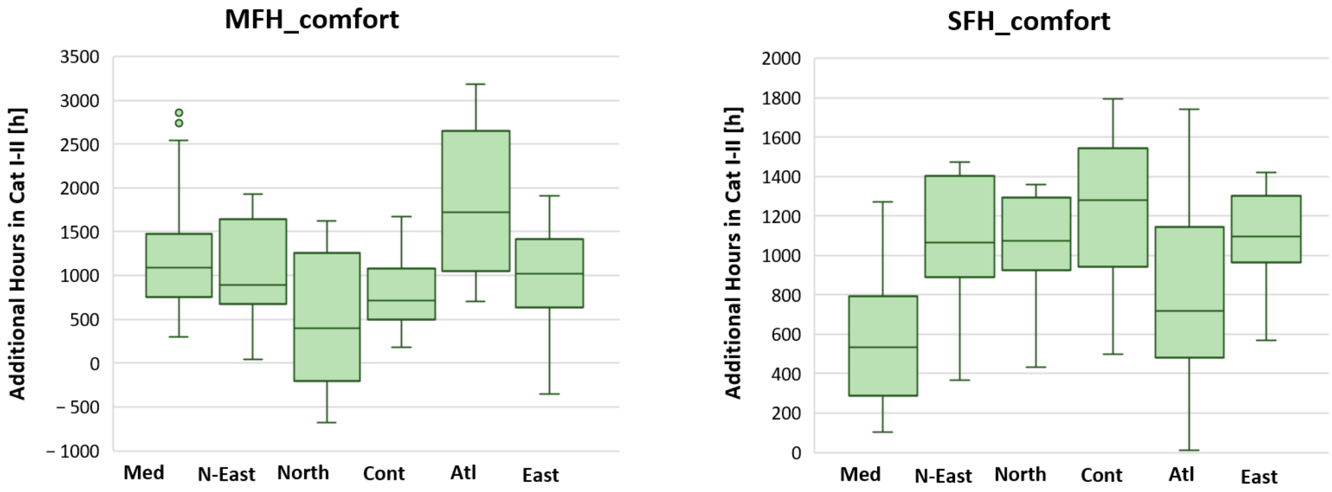


Figure 4. Box plot of thermal comfort conditions for SHF and MFH.

In particular, the additional costs relate to the user preferences, and are structured according to five main categories, namely: the type of cladding, the mounting system, the removal of existing façade, the anchoring type, and the transport. Concerning the cladding, the variant ranges from the most economical finishing usually applied, that is a layer of plaster on a non-combustible board (around 107 €/m^2), towards the ventilated façade with timber cladding (148 €/m^2) and the ventilated façade with high-pressure laminated panels (254 €/m^2). The façade can be installed using scaffolding or a lifting platform, both coupled with the use of crane, that have similar costs impact (respectively, 32 and 33 €/m^2). The removal of the existing façade has a limited impact on the cost, on average it is estimated at around 9 €/m^2.

The most significant factor that affects the costs of the façade is represented by the anchoring system that depends on the structural stability of the existing building and can vary from around 65 €/m^2, in the case of hanging on existing wall structure, to 425 €/m^2 if a dedicated foundation needs to be created for supporting the new façade element.

Finally, the cost for transportation varies according to the distance of the building from the production site: if it is lower than 50 km, the impact on the façade is around 13 €/m^2, from 50 km to 250 km around 37 €/m^2 and for transport farther than 250 km 45 €/m^2 (Figure 4b).

Finally, to consider differences between European construction costs, proportionality cost factors have been used to convert calculated costs, which are referred to the German market according to the identified sources, and to other European countries. The factors have been provided by the European Construction Cost platform (ECC) (http://constructioncosts.eu/cost-index/ access date: 1 January 2021) as reported in Table 3.

Table 3. Construction cost indexes throughout Europe (source http://constructioncosts.eu/cost-index/ access date: 1 January 2021).

Country	Cost Index	Country	Cost Index
Germany	100.00%	Geocluster East—Hungary	55.10%
Geocluster North—Norway	166.36%	Geocluster Atl—Ireland	81.95%
Geocluster Cont—The Netherlands	84.87%	Geocluster N-East—Poland	67.91%
Geocluster Med—Spain	72.99%		

2.3.4. Construction Time

One of the main barriers affecting the uptake of deep renovation is the duration of the construction site and the consequent disturbance for the building occupants. To cope with this issue, the European Commission is fostering the development of industrialised technical solutions for speeding up the renovation process. Including the time estimation related to different renovation packages is crucial to provide a benchmark for adopting this parameter as a benchmark for the decision-making process. Table 4 reports the reference values for the renovation time assessment adopted for including the indicator in the repository. It is important to underline that this evaluation focuses on the cost for the renovation of the façade and the potential integrated systems.

Table 4. Renovation time of different technical solutions.

Operation	Technical Solution	Construction Time
Facade mounting system	Lifting platform + crane	0.41 h/m^2
	Scaffolding + crane	0.27 h/m^2
Removal of old facade cladding	No removal	-
	Yes removal	0.15 h/m^2
Anchoring type for prefabricated facade	Vertical structure anchoring	0.25 h/m
	New Foundation	1.08 h/m
PV system	Façade integrated PV system	0.017 h/m^2
Mechanical ventilation system	Façade-integrated decentralized ventilation system with heat recovery	0.017 h/m^2
	Centralized balanced AHU with heat recovery (ducts integrated in the facade)	0.39 h/m^2

3. Use of the Repository as Support for the Decision-Making Process of Renovation

The renovation package repository aims to provide a support for improving the preliminary design phase of a renovation process. One application deals with the provision of a general overview of the achievable performances in terms of different KPIs for each building typology and reference geocluster (some examples of overall reachable targets reported in Figures 2 and 3). In this case, the interested stakeholders are policy makers, building owners and real estate managers that can have a quick vision of the potential performances of the building after renovation.

Another application is the support for selecting the renovation package most in compliance with the priorities and needs of the stakeholders. In this case, the targets are the designers and technicians involved in the renovation plan that through the repository can present a series of variants to the final users. In this perspective, the repository can also be used by the technology providers to demonstrate the performances of their products according to the five thematic areas and different climatic contexts. In particular, the industrialised façade manufacturers can compare the performances of technical solutions dealing with the integration of different components.

According to the target stakeholder, it is possible to select different renovation priorities and to define a specific decision-making path.

In the following, two approaches based on different decision paths are presented for an exemplary case (i.e., MFH in Continental-Western geocluster), to highlight how the renovation priorities can bring to different solutions and final performances.

The first decision-making path sets as a priority a primary energy consumption target, followed by comfort improvement expectations and CO_2 emissions. Finally, the selected renovation packages have been listed according to the initial investment cost. Figure 5 shows the decision-making path and the performances of the technical variants during the filtering process.

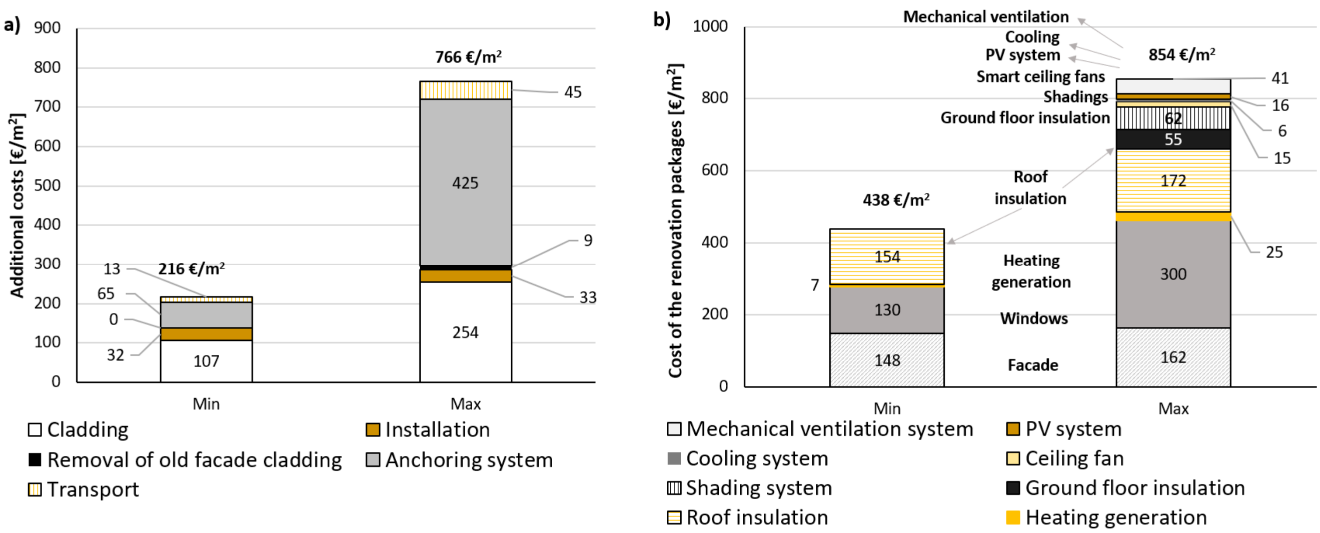


Figure 5. Breakdown of the adopted costs for unit surface (**a**) Energy saving components; (**b**) additional costs.

The identified priorities allowed the identification of 54 solutions that comply with the selected targets. Among them: 27 integrate an optimised photovoltaic system, 34 are heated with a heat pump and 20 with a traditional boiler, and 34 present a cooling system and/or the ceiling fans. Concerning the envelope features, all the selected solutions integrate a shading system (that is essential for reaching an adequate thermal comfort level during summer), and 32 present the highest insulation level (U-value 0.1 W/(m^2 K)).

In this way, the user has a selection of potential renovation packages that meets the expected outcomes with an indication of the costs and duration of the construction site.

Table 5 shows the renovation features of the selected technical solutions, respectively, with the lowest and with the highest investment cost (namely first and fifty-fourth technical solutions) and the associated duration of the building site for the installation of the façade system and integrated elements. In particular, the selected solutions present the integration of the mechanical ventilation ducts in the prefabricated façade.

Table 5. First and last selected options with decision path 1.

Renovation Features	Path 1 Technical Solution 1	Path 1 Technical Solution 54
Façade	PREFABRICATED FAÇADE (U = 0.2 W/(m^{2}K))	PREFABRICATED FAÇADE (U = 0.1/(m^{2}K))
Window	Double glass Low-e	Triple glass
Shading system	Y (Smart)	Yes
Ceiling fan	No	Yes
Cooling system	No	Yes
PV system	No	Yes
Heating generation	Gas boiler	Heat pump
Mechanical ventilation system	Centralised AHU+HR	Centralised AHU + HR
Cladding type	Rendered facade	Ventilated + facade panels
Mounting system	Lifting platform + crane	Scaffolding + crane
Removal of old facade	No	Yes
Anchoring type	Facade mounted	New Foundation
Roof insulation type	Normal insulation	Timber prefabricated roof
Investment [€/m^2]	253	415
Duration of the installation [days]	68	73

In addition to the renovation technical features that directly affect the energy performance, the cost and duration are determined according to the user preferences for the finishing (ventilated façade, cladding type, etc.) and the building features that defines the anchoring type and the mounting system. Within this decision path, it has been estimated that the distance between the building to be renovated and the façade production site shorter than 50 km, while the whole repository includes three scenarios: <50 km, 50–250 km, >250 km.

The renovation costs present a wide range from 253 €/m^2 to 415 €/m^2, since the decision path did not include specific requirements on the investment, and the solutions include several innovative technologies.

Figure 6 shows the second decision path that starts with the identification of an investment cost limit leading to select 258 solutions (including the technical and user preferences) and then the requirements on primary energy, comfort improvement and CO_2 emission follow.

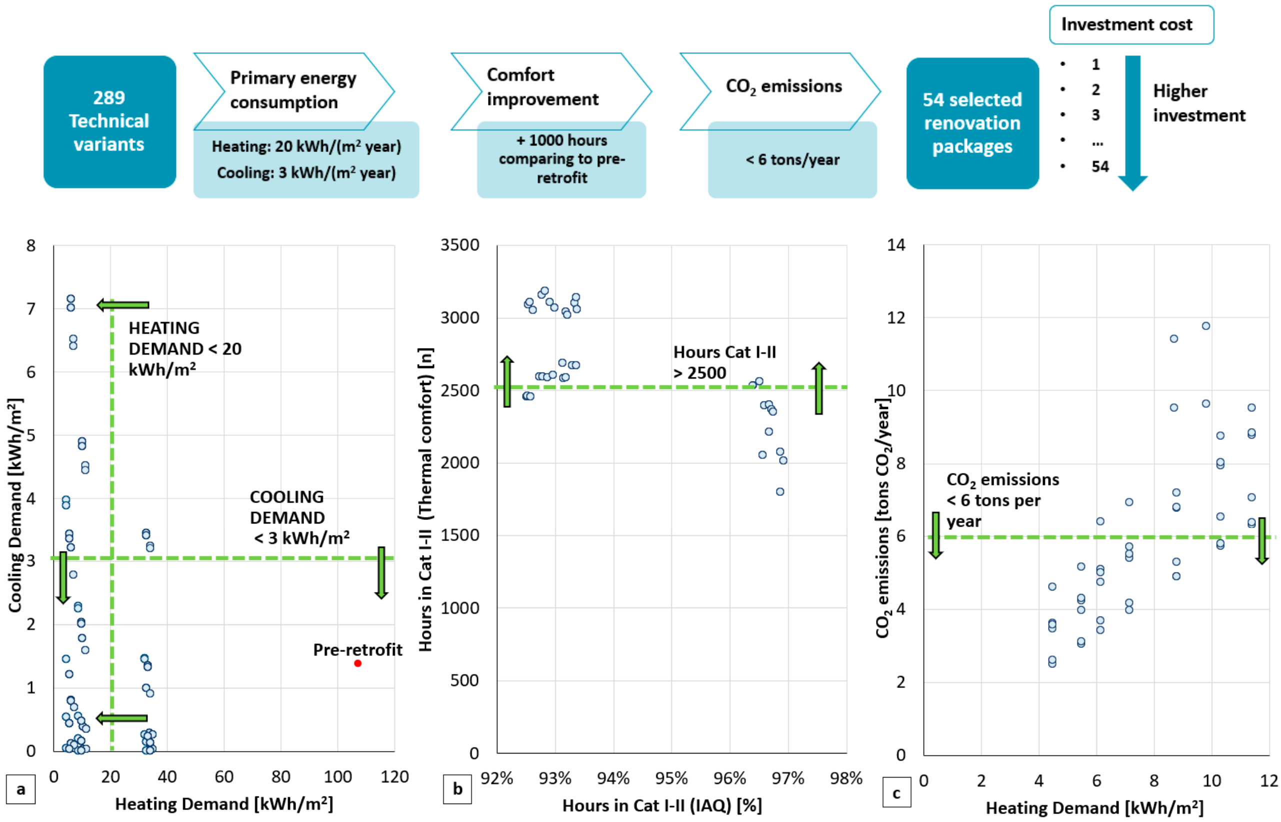


Figure 6. Filtering process for selecting the renovation packages in Continental *Geocluster*: (**a**) Priority 1: reduction in heating and cooling yearly energy demand, (**b**) Priority 2: improvement of comfort conditions, (**c**) Priority 3: reduction in CO_2 emissions.

The second decision path (Figure 7) leads to select four technical solutions which include a limited number of renovation technologies due to the initial investment cost threshold. In any case, the technical solutions included in the repository allow to reach the deep renovation target in terms of primary energy savings and ensure decent comfort conditions. The decision-making path led to the most suitable solutions according to the specific need of the stakeholders, allowing for an accessible performance comparison (Table 6).

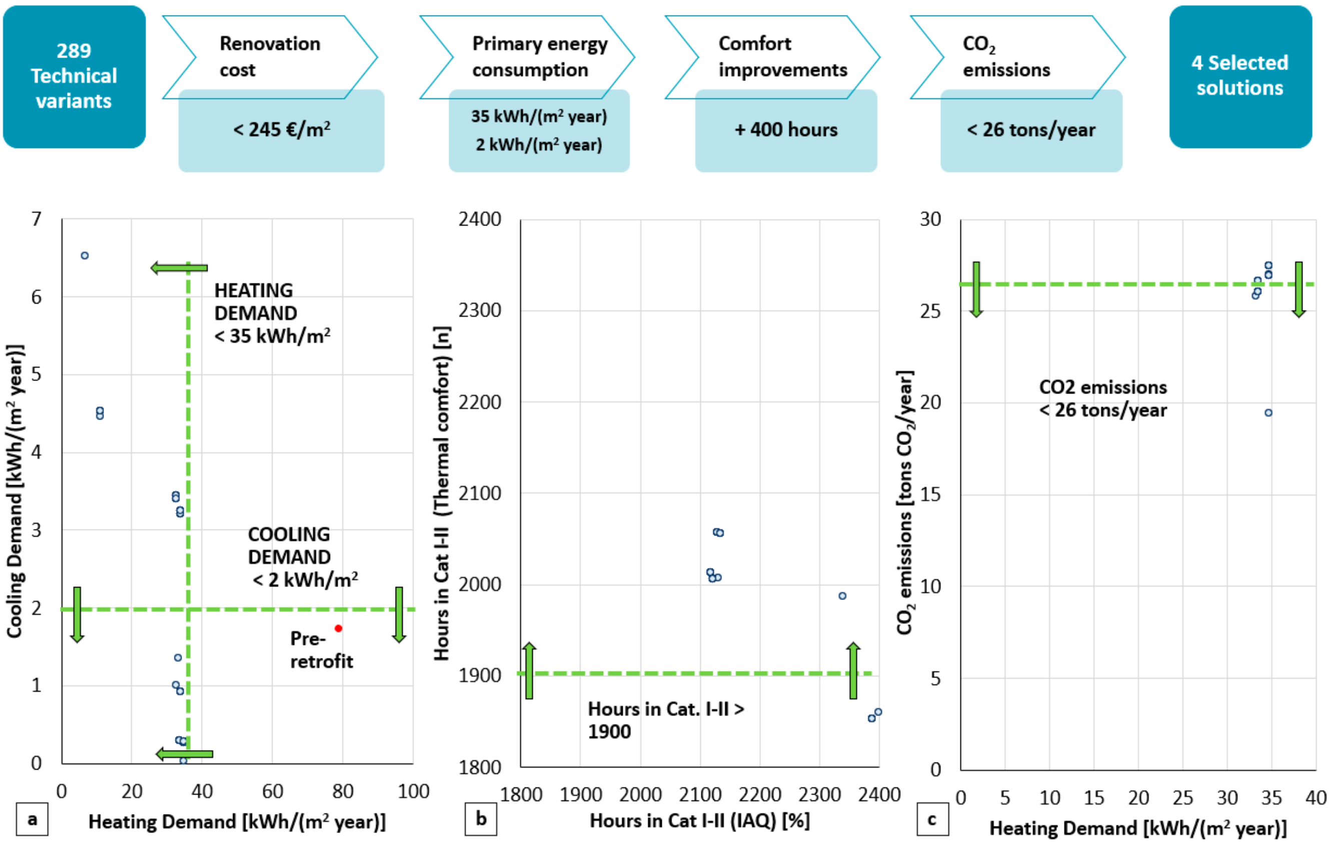


Figure 7. Filtering process for selecting the renovation packages in Continental Geocluster: (**a**) Priority 2: reduction in heating and cooling yearly energy demand, (**b**) Priority 3: improvement of comfort conditions, (**c**) Priority 4: reduction in CO_2 emissions.

Table 6. Selected options with decision path 2.

Renovation Features	Path 2—Technical Solution 1	Path 2—Technical Solution 2	Path 2—Technical Solution 3	Path 2—Technical Solution 4
Facade	PREFABRICATED FACADE (U = 0.2 W/(m^{2}K))	PREFABRICATED FACADE (U = 0.2 W/(m^{2}K))	PREFABRICATED FACADE (U = 0.2 W/(m^{2}K))	PREFABRICATED FACADE (U = 0.2 W/(m^{2}K))
Window	low E double glazing	triple glazing	low E double glazing	triple glazing
Shading system	Smart control strategy	No	Smart control strategy	No
Ceiling fan	No	No	No	No
Cooling system	No	No	No	No
PV system	No	No	No	No
Heating generation	Heat pump	Gas boiler	Heat pump	Gas boiler
Mechanical ventilation	No	No	No	No
Cladding type	Rendered facade	Rendered facade	Rendered facade	Rendered facade
Mounting system	Lifting platform + crane	Lifting platform + crane	Scaffolding + crane	Scaffolding + crane
Removal of old facade cladding	No	No	No	No
Anchoring type	Facade mounted	Facade mounted	Facade mounted	Facade mounted
Roof insulation type	Normal insulation	Normal insulation	Normal insulation	Normal insulation
Investment cost [€/m^2]	242	242	243	243
Duration of the facade installation [days]	35	35	23	23

4. Discussion

Defining a repository of deep renovation packages requires a series of steps for identifying the target of the renovation, the boundaries of the analysis and for selecting the most relevant results. This article proposes a methodology that has been applied for setting up an EU-wide repository of deep renovation packages and related performances for residential buildings.

The complexity and the size of the targeted building stock stated, the results present some limitations due to the approximations introduced for the analysis. In particular, the determination of the construction costs for each country represents a significant challenge since the lack of available databases and EU-wide benchmarks for labour and materials costs. On the other hand, the adoption of reference countries and archetypes, representing a building type and construction period, does not allow for considering in detail the specificities of each building (i.e., peculiar construction features and renovation needs) and the related boundaries (i.e., climate conditions). In this regard, the reliability of the results could not allow identifying the performances of a specific renovation package in each building of the European building stock for the purpose of a detailed design stage.

Nevertheless, the developed repository presents a selection of deep renovation packages and provides a preliminary overview of the ranges of achievable performances, coupled with foreseen costs, in different contexts. This information is very relevant in a preliminary design phase when there is the need to inform the stakeholders about the achievable targets and comparing different solutions.

On the other hand, the repository enables a comprehensive overview of the performances of deep renovation packages including specific technologies, among all industrialised elements, whose implementation requires significant investments. In fact, the usual approach of existing databases focuses on potential energy savings and related investment costs [28] that usually represent barriers for deep renovation [9]. The provision of a wide range of indicators, including energy, comfort, cost, CO_2 emissions and construction time, allows driving the stakeholder towards a more aware decision-making process, essential to enhance high-investment solutions.

Moreover, as described in Section 3, the repository may represent a tool for enabling a tailoring process of the renovation packages according to the stakeholders' needs. The two presented decision-making paths set up different expected performances and renovation priorities, leading to the selection of specific packages matching the foreseen requirements.

5. Conclusions

This work presents the approach for creating a repository of deep renovation packages including multicriteria indicators focused on energy, comfort, environmental, economic and construction time performances.

The results are assessed by means of detailed transient simulations for a set of reference buildings. The analysis is performed according to the boundary conditions of representative countries across Europe as identified by the application of the geocluster approach. The analysed renovation packages include a set of technologies based on industrialization coupled with traditional interventions for the improvement of the envelope performances, HVAC efficiency and exploitation of renewable energy.

Despite the analysis based on representative boundary conditions and buildings, the relevance of the repository to support the uptake of deep renovation and its decision-making process is significant. In the general framework of the European Renovation Wave, there is a wide potential application of the defined deep renovation package repository as a support for boosting the stakeholders and for facilitating the preliminary design phase. In fact, an overall general performance figure can support the users towards the renovation of their houses and represents a reference for the designers for a preliminary estimation of the achievable targets as well as to focus on the most suitable technical solutions. On the other hand, the assessed performances can be considered for identifying benchmarks for renovation packages with industrialised building technologies and allow an increase in the awareness of their potential benefits as a booster towards deep renovation.

In addition, it is possible to adopt the described methodology to extend the performance assessment to a specific context, where implementing the renovation. Following the definition of the building archetypes of interest, the renovation package scheme and the key performance indicators represent a replicable approach to tailor the definition and performance assessment of the deep renovation packages across Europe.

As a future development, the described methodology will be integrated in a structured decision-support tool that will implement a series of decision paths based on different renovation priorities and will provide the possibility to tailor the results to the specific features of the buildings (starting from the defined archetypes) and context boundaries.

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