Towards a Systematic Approach for Supporting The Design Process of Deep Renovation Packages Based On Prefabricated Façade Technologies

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Abstract

In Europe, the CO₂ emissions generated by buildings can be decreased only by enhancing the performances of existing building, and the principle “energy efficiency first” is strongly promoted by the new EPBD. In order to foster the implementation of the renovation, the process has to become faster and the post-intervention performances should be evaluated with a high level of reliability. This research was developed within the EU H2020 project 4RinEU (www.4rineu.eu) and aimed to develop and evaluate a methodology for comparing the performances of deep renovation packages (RPs), implementing traditional and innovative technologies. This paper focuses on the prefabricated façade component in which active elements such shading systems, single-room ventilation devices, and photovoltaic panels have been integrated. Within 4RinEU, Europe was divided into six climatic geo-clusters. The RPs have been defined for a set of representative residential building archetypes selected from TABULA database, based on the characteristics and renovation needs of the building stock in each geo-cluster. This paper presents the general methodology and the preliminary results of the application to one building archetype defined within the project. The results show that the developed methodology is easily replicable and can be a very useful support in the design phase of these complex renovation interventions.

Introduction

The EU building stock de-carbonization promoted by EU policies is very relevant and it aims to increase the renovation rate towards the 3% (European Commission 2018). To meet this target, the integration of innovative technologies, effective methods and viable investment schemes, based on industrializing the renovation process, are needed in order to optimize the investment and to reduce the construction site impact. 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).

Simulating complex systems and technologies could be challenging, but it is strategic in order to ensure the reliability of the performance evaluation providing a consistent support of the decision-making process.

Previous research focused on the definition of deep renovation packages for EU building stock (FP7 project INSPIRE 2012-2016), (H2020 project More-Connect 2015-2018) (H2020 project P2Endure 2016-2020) (Gustafsson, et al. 2017), (D’Oca et al, 2018) and introduced methodologies for cost-optimal evaluation of the solutions (Dalla Mora, et al. 2018), and in some cases applied a multidisciplinary approach (Serrano-Jimenez, Barrios-Padura und Molina-Huelva 2017). Nevertheless, the definition of a structured and systematic methodology for comparing the overall performances of the solutions was missing in the literature. For this reason, within 4RinEU project, a multi-objectives systematic approach was developed and tested considering the integration of functions in an advanced prefabricated façade system used for building renovation.

The methodology presented in this paper addresses the issue, since it is easily replicable and hence represents a support for the designers in the definition of the most suitable RP according to the boundaries and to the specific building renovation needs.

The RPs have been structured considering the elements that can be integrated within a prefabricated façade system, and each technology is represented by a set of key parameters adopted for the performance assessment. This research focuses on the integration of mechanical ventilation, shadings and photovoltaic systems. For each deep RP, different variants have been defined and evaluated through a parametric simulation campaign.

The assessment is based on a set of indicators grouped into five thematic areas: energy, environment, comfort & Indoor Air Quality, economics, and building site management.

For each selected building archetype in six reference countries of the EU geo-clusters, namely Norway, Poland, Hungary, Spain, the Netherlands, and the UK, 289 parametric simulations are set-up in order to assess the KPIs for comparing the performances of the proposed RP.

The proposed methodology represents a robust structure for assessing the effectiveness of deep RPs, since it provides reliable and shared boundaries and multi-criteria key performance indicators. In particular, the parametrization of the deep RPs supports the decision making process during the early design phase, enabling the comparison of several solutions with a structured

approach. Further than the methodology, 4RinEU will create a database of RPs analysed according to the defined KPIs in the EU context for representative archetype buildings. This paper presents the preliminary results of this activity, describing the approach, the assessment methodology and the application to an exemplary case study.

Methodology

This section describes the steps for evaluating the performances of the RPs, as defined within the project 4RinEU. On first, the main boundaries and modelling assumptions are presented, then the technologies included in the RPs and the simulation for assessing the impact on the project KPIs. In this research, a number of deep renovation technologies were combined into different possible renovation packages that were likely to be energy effective in the European context. Then, Europe was divided into geo-clusters, and representative building archetypes were defined for each geo-cluster. The deep RPs were adapted to each geo-cluster and their performances were tested by means of dynamic thermal simulations. The following sections describe the overall approach of the RP performance evaluation.

Boundaries and Modelling Assumptions

Annual simulations have been performed with hourly time-step using Trnsys (TRNSYS Various contributors 2017). The parametric simulation has been performed with JEplus tool (Zhang 2012).

In the following section the main boundary conditions used in Trnsys are presented.

Infiltration control

The infiltration values of the zones have been calculated in accordance to an empirical method suggested by the ASHRAE K_1 , K_2 and K_3 (ASHRAE 1989) model. Therefore, it has been possible to evaluate the air changes per hour (ACH) in the thermal zones at each time-step of the simulation (Equation 1).

$$ACH_{INF} = K_1 + K_2 * (T_{zone} - T_{out}) + K_3 * V_w \quad (1)$$

Table 1 K coefficients values for infiltration calculation

Constru tion Quality	K_1	K_2	K_3	Description
Loose	0.1	0.023	0.070	Poor construction on older buildings where joints have separated
Medium	0.1	0.017	0.049	Conventional construction procedures for building
Tight	0.1	0.011	0.034	Special precautions have been taken to prevent infiltrations

Where K_1 , K_2 , K_3 are coefficients, T_{zone} is the temperature of the thermal zone in [°C], T_{out} is the temperature of the outdoor ambient in [°C] and V_w is the wind velocity in [m/s].

ASHRAE indicates different values of the K coefficients (Table 1) depending on the air tightness quality of the building envelope.

In this study, loose quality has been assigned to the existing case, while tight quality to the retrofitted condition.

Natural ventilation

In this model, the proposed strategy links the window openings to the hour of the day, zone occupancy and the indoor and outdoor temperature. The opening from 7:00 to 21:00 occurs with ambient temperature between 18°C and 28°C and if indoor temperature is out of the range 20.5°C and 26°C. During night (22:00 to 6:00) only if outdoor temperature is between 20.5°C and 25°C. Natural ventilation is designed to provide 2 ACH.

Heating system – existing condition

The heating system has been modelled in a simplified way, by assigning an efficiency to the building sub-systems. In the case of existing building, where the system is supposed to have low performances, low efficiency values have been assigned to the emission (0.9), regulation (0.94), distribution (0.97) and generation (0.82) of the heating system. On the other hand, these efficiencies have been increased in the retrofit case. All the adopted values have been taken from the UNI113000-2 2008.

The chosen set point for heating system was 20°C.

Moreover, in order to estimate the power capacity of the heating system to be installed, a preliminary steady state calculation has been performed for each geo-cluster, taking into account transmission and ventilation losses. In this way, the maximum power for the heating system has been designed.

Internal gains

The occupancy, appliances and lighting profiles were generated using a stochastic model (Widén und Wäckelgard 2010). 20 typical occupancy and use profiles (absent / present_active / present_inactive) are proposed and have been randomly selected for representing the modelled zones (Pernetti, Prada and Baggio 2013) (Pernetti, Prada and Baggio 2014).

Table 2 Internal gains parameters

Parameter	Value	Unit
People density	0.04	[pers/m ²]
Electric equipment power density	3	[W/m ²]
Light power density	3.2	[W/m ²]
Convective fraction of sensible heat gains from persons	0.42	-
Convective fraction of sensible heat gains from electric equipment	0.73	-
Convective fraction of sensible heat gains from lighting	0.60	-
Sensible heat gains form persons	252	[kJ/h]
Latent heat gains form persons	0.08	[kg/h]

Table 2 reports other parameters needed in order to calculate the gains to be assigned at the internal zones. They have been taken from literature or technical documents (e.g. EN 16798 for people, electric equipment and light density in residential areas).

Model set-up

Different renovation packages

This section describes the renovation packages analysed. The focus is on the use of a prefabricated timber framed multifunctional façade. These prefabricated modules are designed to be anchored to the existing building envelope and represent the new “skin” integrating functions (i.e. building services and components) and able to strongly increase the lifetime of the building.

The different combinations of the prefabricated façade with the different integrated components and services represent the renovation packages.

In particular, the following variants integrated in the façade have been considered:

- Timber prefabricated element: two types of façade module for retrofit have been considered; they are both composed by a timber frame and cellulose fibre insulation in different thicknesses, ensuring two different values of thermal transmittance.
- Window: two typologies of windows have been used, namely a double low emission glazing and a triple glazing, combined with a high performances frame.
- Ventilation: decentralized or centralized ventilation machines have been considered in the study, considering that the former can be completely integrated in the prefabricated façade and the latter can partly be integrated (e.g. the ventilation ducts)
- BiPV: photovoltaics panels
- Advanced shading system: an automated external shading system

Moreover, we analysed also three further technologies, not strictly related with the prefabricated façade, but studied by 4RinEU within the renovation packages:

- Cooling system
- Heat pump
- Ceiling fan

Shading control

A shading control system is present both in the existing and in the retrofitted configuration. The main difference is that, while in the existing condition the control is based only on the external incident radiation, in the retrofitted condition the shading system is also activated depending on the indoor and outdoor temperatures.

Traditional heating system – retrofit condition

In the case of retrofit building condition, a condensing boiler has been chosen as a traditional heating system; it has been selected in order to have high performances, therefore high efficiency values have been assigned to the

emission (95%), regulation (99%), distribution (99%) and generation (97%) of the heating system.

Heat pump

In the retrofit condition, the condensing boiler was replaced with a heat pump. A coefficient of performance (COP) of 3 has been chosen for the component as this is a typical value of current systems.

Cooling system

A cooling system with unlimited capacity has been included in the retrofit scenario of the models. Working hours have been set from 8:00 to 16:00 with setback set point during night. According to the ASHRAE 55 adaptive model, considering the 80 per cent acceptability upper limits, the set point for cooling is variable and depending on the weakly mean outdoor temperature (T_m). The set point is calculated as follows:

$$T_{\max(80\%)} = 21.3^{\circ}\text{C} + 0.31 \cdot T_m \quad (2)$$

Centralized mechanical ventilation

A possibility for the retrofitted scenario is to have a centralized mechanical ventilation system.

Considering the example of the multi-family house, one machine managing 600 [m³/h], consuming 140 W, per each floor has been provided. This accounts for 0.25 [ACH] per zone. This system enables also a heat recovery between inlet and outlet air with an efficiency of 0.81.

These values have been taken from a commercial centralized ventilation unit. Two possibilities for infiltration control have been set. On the one hand, no infiltration have been supposed, due to the effect of over-pressure in indoor rooms because of mechanical ventilation. In this condition, in order to ensure the right amount of indoor ACH, a doubled airflow from mechanical ventilation machine has been considered. In the second option, the infiltration rate is taken into account without considering the over pressure effect induced by mechanical ventilation machine.

Decentralized mechanical ventilation

In order to have a mechanical ventilation system in the retrofit, another option is the use of a decentralized system. These machines consume up to 20 [W], and can provide 42 [m³/h] of airflow with 0.7 heat recovery. When this technology has been used, the chosen ACH per apartment were 0.23 [ACH].

These values have been taken from a commercial decentralized ventilation unit.

PV panels (roof & façade integrated)

PV panels placement for renovated cases have been optimized for each geo-cluster and different building geometries. The optimization has been performed with a Eurac internally developed tool, namely ‘Early Reno’ (Lovati, Adami und Moser 2018). 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 in order to have the highest net present value (NPV) within a defined period. The available positions of the PV panels were given on the

roof and on the south façade. The chosen module dimension has been 1.44 m² with a peak power of 255 W.

Ceiling fan

Another possible improvement applicable to the retrofitted scenario was smart ceiling fans. Considering that 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 simulated with the method proposed by (Babich, et al. 2017). Therefore, in order to account for this effect, in case of ceiling fans operations at 0.9 [m/s], the cooling set point has been increased by +1.8°C.

Analysis of the EU building stock

Geo-cluster division

In order to provide a European framework for the parametric analysis of the RP performances, Europe has been divided in six geo-clusters, according to the 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) and climatic conditions. National boundaries have been used since they influence technical constraints and legislative requirements in case of renovation (Figure 1). Each geo-cluster includes either a demo case or an early adopter (EA) building where the 4RinEU renovation packages will be integrated respectively with a real implementation (demos) or a feasibility study:

- Geo-cluster 1: Northern Europe countries with cold climate and prevalence of single-family houses – reference country: Norway
- Geo-cluster 2: Northern East Europe countries with cold climate and large amount of multi-family houses built between 1960 and 1990, with prefabricated concrete panel – reference country: Poland
- Geo-cluster 3: Continental West and central with continental climate. The building stock is mainly composed by single-family houses and there is no prevailing construction period, thus the stock presents different construction features (masonry, concrete or prefabricated structure) – reference country: The Netherlands
- Geo-cluster 4: Continental East, main building typology is single-family with a significant amount of multi-family houses built after the 2nd World War with prefabricated concrete structure – reference country: Hungary
- Geo-cluster 5: Mediterranean countries with warmer climate, where the building stock is split almost equally in single and multi-family houses built in different construction periods mainly with masonry or concrete structures – reference country: Spain
- Geo-cluster 6: Atlantic zone with cold oceanic climate and single-family houses as main building type - reference country: the UK

Definition of Building Archetypes

For each geo-cluster, four representative building archetypes in the respective reference country have been selected. The source for this selection was the national building typologies developed as part of the Tabula project (IEE Project TABULA 2018). All 4RinEU archetypes are selected among these example buildings. However, in order to keep the number of models manageable, four main geometries have been identified and used for the simulation in each geo-cluster (Table 3).

Figure 1 Geo-cluster division

Table 3 Simulated geo-cluster geometries

Geo-cluster Geometry	Building characteristics
	Archetype: TERRACED HOUSE (TH) Reference floor area: 88 m ² Floor Height: 2.8 m
	Archetype: SINGLE FAMILY HOUSE (SFH) Reference Floor Area: 228 m ² Floor Height: 2.5 m
	Archetype: APARTMENT BLOCK (AB) Reference Floor Area: 1330 m ² Floor Height: 2.6 m
	Archetype: MULTIFAMILY HOUSE (MFH) Reference Floor Area: 3456 m ² Floor Height: 2.8 m

Although the geometries were identical in each geo-cluster (e.g. windows number and dimensions), the

envelope's characteristics have been varied according to the typical features of each geo-cluster.

Technical data for the archetypes has been extracted from the Tabula data tool. Therefore, existing building's envelope characteristics (i.e. wall, roof, window glazing and window frame) have been defined for each geo-cluster.

Job list & simulations

The different combinations between renovation packages have been studied performing a parametric analysis per each of the 4 building geometries in the 6 climatic areas. The software used has been JEplus. This tool is able to read specific strings referring to the parameters to be changed within the *.dck and *.b17 execution files of Trnsys. Then, it assigns to these parameters the corresponding values given by the user in a "job list". Each row of this file corresponds to a simulation and it contains the values of each of the parameters to be specified.

In Table 4, the parameter list of the multifamily house archetype in the Netherlands is presented as an example.

Table 4 Parameter list

PARAMETER	Involved controls/technologies	COMBINATIONS
RETROFIT CONDITION	Shading control, infiltration control, traditional heating system efficiency, cooling system operability	1
TRADITIONAL HEATING SYSTEM	Heating performed by a traditional system	2
HEAT PUMP HEATING SYSTEM	Heating performed by an heat pump	
NO MECHANICAL VENTILATION	No mechanical ventilation is used	3
DECENTRALIZED VENTILATION MACHINE	Mechanical ventilation provided by a decentralized system	
CENTRALIZED VENTILATION MACHINE	Mechanical ventilation provided by a centralized system	
PV INTEGRATED	PV panels presence within the building	2
CEILING FAN & COOLING SYSTEM	Ceiling fan presence within the building (different working combinations)	3
RETROFIT WALL TYPOLOGY	Two different layouts of the prefabricated panel performing the renovation of the envelope	2
WINDOW TYPOLOGY	Two different new window typologies to be installed	2
INFILTRATION	Takin into account infiltration effect	2
TOT =288 + 1 (existing case)		

Only parameter referring to the possible renovation packages are shown, because the existing condition of the building has been simulated apart.

Description of selected KPIs

The performances of the 4RinEU deep renovation packages are evaluated using a set of Key Performance Indicators (KPIs), set as the outputs of the parametric study.

The evaluated thematic areas considered within the project are:

- Energy: indicators dealing with the energy consumptions of the building and with the energy produced with Renewable Energy Sources (RES). In particular, both energy demand, energy consumption and primary energy consumption have been considered for all the energy-consuming technologies within the building or integrated in the renovation packages.
- Comfort and Indoor Air Quality (IAQ): indicators dealing with users comfort and indoor air quality.
- Environment: evaluation of the environmental impact of the building after the renovation
- Economic issues: evaluation of the NPV of the renovation calculated along 25 years from the intervention; moreover, the investment cost and energy cost for the renovation.
- Building site management: indications on the whole renovation time, differentiating between production of the element and complete intervention.

In this paper, the chosen KPIs are limited to those presented in Table 5:

Table 5 KPIs – Simulation Outputs

Energy	
Net Energy demand for heating	[kWh] - [kWh/m ²]
Final Energy Demand (considering the efficiency of each subsystem of the heating plant)	[kWh] - [kWh/m ²]
Net Energy demand for cooling	[kWh] - [kWh/m ²]
Final Energy demand for cooling (considering the efficiency of each subsystem of the cooling plant)	[kWh] - [kWh/m ²]
Net Energy demand for DHW production	[kWh] - [kWh/m ²]
Final Energy demand for DHW production	[kWh] - [kWh/m ²]
Energy demand for ventilation (due to ceiling fans operation and mechanical ventilation)	[kWh] - [kWh/m ²]
Energy produced via PV system	[kWh] - [kWh/m ²]
Electricity self-consumption	[kWh] - [kWh/m ²]
Energy produced via ST systems	[kWh] - [kWh/m ²]
ST energy balance	[kWh] - [kWh/m ²]
Global Building Energy demand	[kWh] - [kWh/m ²]
Environment	
CO ₂ Emissions for Heating & Cooling	kg CO ₂ /year
Comfort & IAQ	
IAQ n°hours categories – Adaptive comfort model (EN15251:2007)	[h]
(to be used during cooling season)	
IAQ n°hours categories – PMV model (EN15251:2007)	[h]
(to be used during heating season)	
Overheating Degree Hours (>28)	[°C]
Severe Overheating Degree Hours (>29)	[°C]
CO ₂ concentration categories (EN15251:2007)	[h]

Results

The results of the simulations are organized in a database containing, for each building, the job list and the assessed KPIs. The added value of the database is the possibility to prioritise the RP according to the category of interest (comfort/energy/environment).

The following section reports a couple of exemplary charts summarising the results, representing the RP performances in one archetype, i.e. the multifamily archetype in the Netherland (Continental Central geocluster) and showing relations between different KPIs.

In the graphs, colors of the marker are used to distinguish between different combinations of retrofit wall ($U_{\text{value}} = 0.1 \text{ W/m}^2\text{K}$ or $U_{\text{value}} = 0.2 \text{ W/m}^2\text{K}$) and window typologies (triple glazing filled with Argon or low-emissive double glazing).

In each graph, different groups of results are highlighted in order to recognize easily the effects of the application of different technologies and simulation settings.

By comparing the performances of the renovation packages it is possible to highlight which of them suits more effectively the target of the users, thus it will be easier to define the technologies to be applied in case of renovation.

Figure 2 and Figure 3 present, as examples, an analysis on the results coming from the parametrization. A cross analysis using such graphs can lead to the definition of the best scenarios in a specific contest.

Figure 2 Heating and Cooling demand [kWh/m²]

Figure 3 Number of occupied hours in CO₂ ppm categories for Indoor Air Quality Evaluation (EN15251) in the complete set of simulations

This general overview could be the starting point for a more detailed analysis in the design phase. Hence, using a filtering process on all the possibilities based on a priority criterion, the best configuration could be defined.

One of the following step of the project is developing a user interface in order to select and compare easily the RPs in terms of different performances.

Conclusions

The approach presented in this paper represents a comprehensive methodology for comparing the effect of different RPs in different climatic context and building typologies, as defined and adopted in the H2020 project 4RinEU. It is easily replicable and can represent an effective support for the designers in the definition of the most suitable RP according to the boundaries and to the specific building renovation needs.

On one hand, the results of the application of the methodology to the selected building archetypes represent a demonstration of the consistency and of the replicability of the methodology. On the other hand, at the end of 4RinEU project, the results will be stored in a database of technical solutions and performance assessment, and will be a ready reference for the designers to make a preliminary evaluation of the potential performances of deep RPs according to the boundary conditions and the building renovation needs across Europe.

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