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New step-by-step retrofitting model for delivering optimum timing

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HIGHLIGHTS

- Model to deliver the optimum timing of step-by-step retrofitting activities.
- Comparison of interdependency of the steps, particularly due to heating systems part- and full-load operation.
- Comparison of step-by-step with single-step renovation by using the cumulated energy savings as metric.
- Case study considers real-life individual building renovation roadmaps.

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ABSTRACT

Although the Energy Performance of Buildings Directive 2018/844/EU introduced the building renovation passport and by such proposed to consider step-by-step renovation, a literature review could not identify any explicit step-by-step retrofitting optimisation model. Therefore, the present study seeks to explore the following research questions: which indications regarding the optimum timing of renovation steps can a net present value maximising model deliver; how are model's results impacted by the interdependency of renovation steps and by homeowner's budget restrictions. The model relies on three pillars: homeowners' budget restrictions; building material ageing processes; and interdependency between the retrofitting steps. Implemented as a mixed-integer linear program, it maximises the net present value of households' energy-related cash flows, and delivers the optimum timing when each step should be performed. As input data, five real-life building renovation roadmaps were used. The appropriate metric to assess building's retrofitting energy savings is also discussed. When comparing both single-step and step-by-step approaches, the step-by-step presented 11–22% higher cumulated energy savings. Results also show that a renovation period would last between 1 and 14 years and 2 to 11 years, depending on whether interdependency of measures is considered. This has direct implications on the improvement of building stocks' energy efficiency, and consequently, the achievement of decarbonisation targets set for 2050. In this context, the model delivers a more concrete time horizon perspective in regards to the achievement of these targets. Future work will include quantifying the economic effects of interdependency of steps and expanding the analysis for varies techno-economic building typologies.

1. Introduction

Tne European Union has identified the building sector as one of the critical sectors for achieving the energy and climate policy targets, as buildings are currently responsible for about 40% of energy consumption and 36% of CO_2 emissions in the EU [1]. Aiming to accelerate building stock decarbonisation, the recast of the Energy Performance of Buildings Directive (EPBD) 2018/844/EU introduced the building renovation passport in Article 19a, an instrument that provides a long-term and step-by-step deep renovation roadmap for individual buildings. Until now, many policy instruments have focused on the single-step approach for performing deep renovation, where all renovation measures are performed at once. However, different studies [2–3] have shown that most renovation activities are actually performed step-by-step, which means that the renovation measures are not performed at the same time. Cischinsky and Diefenbach collected evidence in 2010 [4] and 2018 [5] based on the building stock renovation activities in Germany, which showed significant evidence of a step-by-step tendency in renovation. This might be related to different barriers such as the homeowner's ability to pay for the entire renovation project, a

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particular influential family situation, or a lack of knowledge about how to perform the measures. Therefore, the building renovation passport is definitely an important instrument at the EU level to support deep renovation of existing buildings because it helps bridge the gap between real renovation processes and the EU-targets for building stock decarbonisation; and it recognizes the step-by-step approach as another possible approach to perform retrofitting, that could later enable the designing of targeted policy schemes [6]. The building passport and step-by-step renovation roadmap were explored by the EU H2020 iBRoad Project [7], which developed tools to support energy auditors on developing individual building renovation roadmaps (more details about the project activities are presented in chapter 4). The step-by-step deep renovation roadmap itself is a long-term plan that guides homeowners through the renovation process, and helps them to avoid the risk of lock-in effects by foreseeing and sequencing future renovation activities [8–9]. When the energy savings potential of the renovation activity is untapped, it is considered an "energy locked-in" renovation. In this case, the building will remain operating at a lower energy efficiency for a considerably long amount of time [10]. For this reason, it is important to long-term plan the renovation activities, exploiting the full energy saving potentials from the beginning. Referring to a homeowner's ability to pay, statistics [11] show that across the EU, household disposable incomes vary between 18,000 euro (Hungary) and 40,000 euro (Luxembourg) from which household expenditures for housing and maintenance correspond to about 30% [12]. These facts provide evidence to the hypothesis that homeowners' abilities to invest in renovation often depend on their financial and lifestyle situations, which determine the retrofitting approach (step-by-step or single-step) [10].

This paper aims to develop and apply an optimisation framework for step-by-step retrofitting, which calculates the optimum timing to perform each step (or package of measures) taking into account budget restrictions, material ageing processes, and interdependency of the steps. The optimum timing is delivered based on the maximised net present value of a household's energy-related cash flow. Additionally, the retrofitting steps' interaction is assessed and compared by analysing two possible model constraints to represent the interdependency of steps. Finally, the outlined model is applied to real-life case studies which consist of five owner-occupied single-family houses. Their actual building roadmaps developed during the EU H2020 iBRoad Project. This paper aims to answer the following three research questions (RQ):

RQ1: Can a step-by-step retrofitting optimisation model that maximises the net-present value of households' energy-related cash flows deliver optimum timing indications?

RQ2: What impact does the interdependency of steps have on the optimum timing in a step-by-step retrofitting model?

RQ3: What impact does the homeowner's budget restriction have on the optimum timing in a step-by-step retrofitting model?

Firstly, the present paper adds to the existing literature by outlining a framework for the step-by-step retrofitting optimisation modelling. It specifically does this by creating more comprehensive modelling for a step-by-step renovation approach. Secondly, it takes into account the homeowner's budget restrictions to invest in renovation. Finally, the model outlined in the present paper can be incorporated or coupled into building stock models. Existing building stock models are for example Invert/EE-Lab [13] and CESAR [14] and they deal with the central question of modelling building stock's energy demand development . When applied to other building typologies, the present model adds to the current state by assessing the relevance of time horizon when the targets can be achieved. As the targets defined by the Long-term renovation strategies (at both EU [15] and national [16] level).

In this paper's context, the term retrofitting will be used (instead of deep renovation) to highlight the positive effect of the renovation activity on the energy savings. Chapter 2 presents a conceptual comparison between single-step and step-by-step approaches to better illustrate the main differences between both approaches. The same chapter presents a literature review of current retrofitting optimisation models. The main reason for discussing the step-by-step approach is because until very recently, policies' instruments have only focused on the single-step approach; however, in 2018 the EPDB introduced the step-by-step approach as another possible strategy for retrofitting buildings. Chapter 3 presents the method by outlining the model and introducing the real-life case studies to which the model was applied. In Chapter 4 presents the case studies. Chapters 5 and 6, represent respectively the results using the case studies and the sensitivity analyses. Chapter 7 discusses model's limitations and next steps. Finally, Chapter 8 presents the main conclusions from this paper.

2. State of the art

This chapter presents a comparison of a single-step and a step-by-step retrofitting approach (section 2.1) and gives a summarized review of current retrofitting optimisation models (section 2.2).

2.1. Retrofitting approaches

Concerning timing, there are mainly two different retrofitting approaches: 1) when the whole package of measures is performed at once (single-step), and 2) when various measures are performed at different times. This second approach can be further divided into sub-categories: room-by-room, measure-by-measure, and step-by-step.

In Europe, some demonstration projects focus on the key concept of building passports, one of which is the EU Horizon 2020 iBRoad project [9]. This project explored many aspects of the step-by-step concept and provided IT solutions for supporting auditors in developing a step-by-step, long-term renovation roadmap for individual buildings, especially for owner-occupied single-family houses [17]. The project tested the developed software tools on real buildings, which will serve as case studies in the present study. The project reports describe how the field test took place [18] and evaluate the implementation of tested tools [19].

Fawcett researched the time dimension of different renovation approaches [20]. Fawcett, Topouzi, Killip and Owen, later analysed the risks related to these approaches [21]. Based on these studies, Table 1 presents a comparison between the single-step approach and step-by-step approach in terms of definition, time-dimension, effects on climate targets, main risks, main barriers, material costs, and labour/installation costs.

Table 1
Comparison between two retrofitting approaches. Source: own compilation.

	Single-step	Step-by-step
Definition	Only major renovation (including whole building envelope)	Retrofit measures performed according to trigger points
Time dimension	At once	Over the years (or decades)
Effects on climate targets	Fast CO_2 emission reduction once the renovation takes place. Cumulated CO_2-emissions depend on the timing of the single-step renovation.	Gradual CO_2 emission reduction
Main risks	If not done right, mistakes take a long time (even decades) to be corrected (lock-in effects)	Avoid missed opportunities and lock-in effects, if the different steps are not carried out correctly
Barriers	Disruption and/or affordability	Lower barrier for single measures
Material Costs	At once – possibility that loans and policy-related incentives are available	Cost-shifting – further measure costs can be partially anticipated and/or postponed
Labor / Installation Costs	At once	Scaffolds and other construction site equipment might have to be mounted more than once

In the step-by-step approach, each step consists of a package of one or more measures. The renovation measures were identified in the literature, based on theoretical studies [22] and real-life experiences [23–25]. They can be mainly divided into envelope measures such as adding insulation layers into walls (internal or external), roof or upper ceiling, and floor or lower ceiling; replacing windows and/or doors; and installing technical system measures (e.g., replacing technical systems - domestic hot water, heating, cooling, lighting and mechanical ventilation - with more efficient ones).

Relevant issues that influence the time aspect of retrofitting are the trigger points. Trigger points are circumstances that initiate a home improvement project that is not necessarily motivated by energy savings [26]. However, trigger points can be seen as an opportunity to improve the home's energy efficiency, as homeowners are more likely to undertake renovation work at these times [27]. Examples of trigger points could be a heritage gain, a boiler breakdown, retirement, marriage, or moving into a new home. In the present framework proposed, the parameters lifetime and ageing processes are used to portray the building material's and technical system's life cycle as representative of a technical trigger point and an influencing factor in defining the optimum retrofitting timing [28]. During a building's life cycle, maintenance and operation activities constantly need to occur to avoid first stages of degradation and failure of the building material [29]. Simultaneously, regular maintenance activities and/or material replacement provide an opportunity for increasing the building's energy efficiency, and, consequently, improving the building's energy performance. These activities may be initiated by unpredictable damages such as breaks, leakages and cracks, or predictable parameters, such as a material's durability that is defined by the material's lifetime. Some studies have proven the effects of trigger points, including one from 2014 by Achtnicht and Madlener that explored the influencing factors on energy retrofit preferences of German homeowners [30]. The authors concluded that most homeowners tend to wait until the end of the building material's and technical system's life cycle before approaching renovation or replacement.

2.2. Retrofitting optimisation modelling

A retrofitting optimisation model aims at calculating the optimum solution between various retrofitting measures (or a combination of them). The optimum retrofit strategy may include ecological (e.g. energy savings, CO_2 emissions, environmental impacts) and economic (e.g. net present value, investment cost, payback time, life cycle costs) objectives and/or restrictions. Many studies about retrofitting models were reviewed to prepare the ground for outlining a framework for a step-by-step optimisation model. Pombo, Rivela and Neila studied the challenges related to building renovations [31] and presented essential insights to be taken into account by retrofitting models. Another study [32] presented a review of tools and models to support refurbishment decisions. Emmerich and Deutz developed a tutorial for multi-objective optimisation [33], which is a method used by other authors ([34;35]) to assess building retrofitting. Other methods used were Monte Carlo Simulation [36] and cost-effective calculation based on operational costs [37]. Next, a more in-depth literature review of the existing models will be presented.

The models have in common that they aim to select the most suitable retrofitting solution, depending on the target benefits. These targets are represented by an objective function that can be single-objective or multi-objective. Most recently, Jafari et al. [38] reviewed at least sixteen studies about energy efficiency decision-making, including multi-objective optimisation and other methods such as a multi-criteria method, a techno-economic evaluation method, and others. The same authors presented an optimisation framework to minimise the future cost of a building (life cycle costs minus initial investment costs). In this approach, the energy savings are indirectly represented by the energy costs, which are part of the life cycle costs. The set of retrofitting measures in their study goes beyond insulation of the building envelope (ceilings, walls, attic insulation). It includes load reduction measures (heating and cooling), controlled measures (i.e. programmable thermostat), and renewable energy options (i.e. solar thermal and solar electricity). Pombo et al. [39] compare different retrofitting solutions using a multi-criteria methodology. This study combines Life Cycle Assessment (LCA) and Life Cycle Cost (LCC) by expressing environmental impacts in monetary values. Here, the minimum investment cost and minimum life cycle savings are determined through a Pareto curve. The chosen renovation measures aimed to reduce space heating and cooling demand by insulating the roof and façade, changing the windows, and installing a heat recovery system. Asadi et al.[40] developed a model to assist stakeholders in defining measures aiming to minimiseaimed at minimising the energy needs for heating, cooling and domestic hot water, and maximising the investment costs. The authors considered a set of retrofit measures, including window replacement, external wall and roof insulation, and installation of a solar collector. Wang et al.[41] proposed a life cycle cost approach that maximises energy savings and net present value (NPV) while minimising the initial costs. The chosen measures were lighting facilities, heat pumps, a chiller, control systems, and other devices focusing on reducing the electricity energy demand. Murray et al. [42] coupled a degree-days simulation with a generic optimisation procedure algorithm and compared both implemented and calculated retrofit solutions. That study aimed at minimising the energy cost and carbon emissions post-retrofit under the consideration of a payback period of a maximum of 5 years and capital investment. The adjustable set parameters were the U-values from attic, external walls and windows, boiler type, and infiltration rate. Table 2 below presents a summary of mentioned models in terms of their objective functions, retrofitting approach, consideration of budget restrictions, and type of model.

Although the models above differ from each other, all methods have in common that they do not present any indication about the timing aspect or any indication as to when the retrofit measures are performed. This leads to the conclusion that they assume that the retrofitting measures are applied simultaneously, so called single-step (or single-stage) retrofitting. Seeing that there is a lack of modelling for step-by-step retrofitting, this study specifically treats timing as a vital relevant factor.

In addition to timing considerations, the present study also focuses on budget restrictions as a relevant factor. On a study about drivers of thermal retrofit decisions, the authors [43] pointed out that the up-front costs are a key barrier to the pursuit of building retrofits, especially in single-family houses. Some authors [38,41] included the budget restriction in their models, but only as a fixed value without a method justification. The budget restriction is addressed in the present work, taking into account the different assets for retrofitting based on the family's income and its share for energy-related expenditures. Moreover, the effect of different budget restrictions on the optimum timing is presented in the sensitivity analysis.

3. Method

The general approach consists of mainly four stages:

Stage I) Outline and implement a step-by-step optimisation model which maximises the net present value (NPV) and delivers the optimum timing of when each step should be performed. To calculate the expected results, a mixed-integer linear optimisation programming code was developed, which includes several constraints including the household's budget restriction, building material ageing process, and the interdependency of the measures;

Stage II) Apply and validate the model for the selected case study buildings. The roadmaps of the studied buildings were developed by energy auditors during the EU H2020 iBRoad project, which enabled the use of input data that is closer to real-life scenarios;

Stage III) Compare the results for different interdependency constraints in order to understand the effect of interdependency on the

Table 2
Summary of analysed literature review on retrofitting modelling.

Source	Title	Objective Function	Retrofitting approach	Budget restriction	Model
Wu et al.,2017 [61]	Multi-objective optimisation of energy systems and building envelope retrofit in a residential community	Minimise annualised costs Minimise life cycle GHG emissions	Single-step	No	Mixed-integer linear optimisation
Jafari und Valentin, 2017 [38]	An optimisation framework for building energy retrofits decision making	Minimise life cycle investment	Single-step	Yes	Nonlinear single objective optimisation
Pombo et al., 2016 [39]	Sustainability assessment of energy saving measures: A multi-criteria approach for residential buildings retrofitting—A case study of the Spanish housing stock	Minimise investment cost Maximise life cycle savings	Single-step	No	Multi-criteria optimisation (or Pareto optimisation)
Asadi et al., 2012 [40]	Multi-objective optimization for building retrofit	Minimise retrofit costs Maximise energy savings	Single-step	No	Multi-objective optimisation
Wang et al. 2012 [41]	A multi-objective optimization model for the life-cycle cost analysis and retrofitting planning of buildings	Maximises energy saving Maximises the discount payback period Minimises initial costs	Single-step	Yes	Multi-objective optimisation
Murray et al. 2014 [42]	Multi-variable optimization of thermal energy efficiency retrofitting of buildings using static modelling and genetic algorithms - A case study	Minimum energy cost Minimum carbon emission Maximum simple payback time	Single-step	No	Three single objective optimisation (multi-variable, not multi-objective optimisation)
Mauro et al., 2015 [62]	A new methodology for investigating the cost-optimality of energy retrofitting a building category	Cost-optimum approach for retrofitting options	Single-step	No	SLABE tool (no optimisation approach)
Fina et al.,2019 [63]	Profitability of active retrofitting of multi-apartment buildings: Building-attached/integrated photovoltaics with special consideration of different heating systems	Maximise net present value	Single-step	No	Mixed-integer linear single objective optimisation
Current study		Maximise net present value	Step-by-step	Yes	Mixed-integer linear single objective optimisation

building's cumulated energy savings for the period up until 2050;

Stage IV) Derive conclusions in relation to the long-term renovation strategy and decarbonisation targets set for 2050 and develop an outlook on further model development steps.

3.1. Model description

The techno-economic retrofitting optimisation model outlined in this paper has the main objective to indicate the optimum timing to perform each step of a step-by-step retrofitting approach, delivered for the maximised net present value [44]. The method relies on techno-economic specifications, as described below:

1) Technical specifications: specification of the renovation measures and their combination (step), identification of building elements' material, specification of material's lifetime according to existing databases, and calculation of material's ageing process;

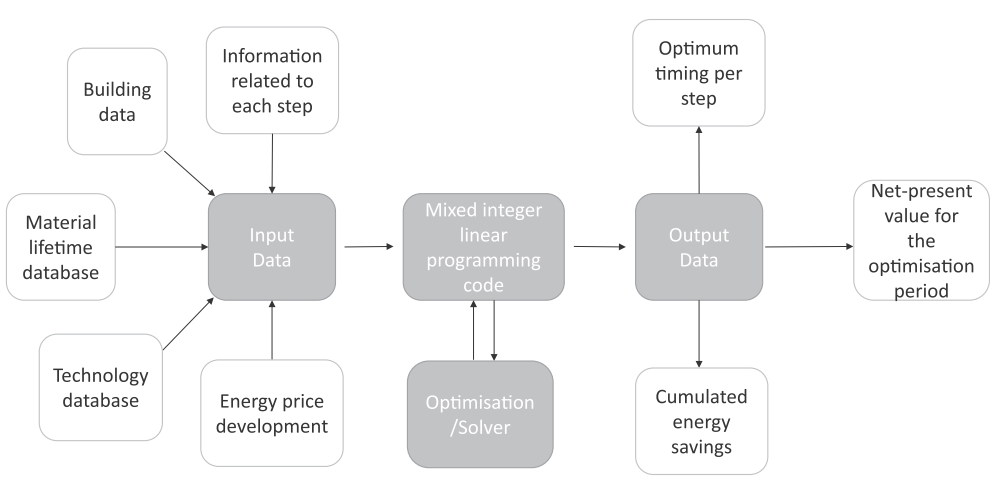


Fig. 1. Step-by-step optimisation model:code architecture.

2) Economic specifications: investment costs per step, energy price development per energy carrier, and homeowner's budget restriction

The present model's primary purpose is to provide a more concrete time horizon perspective regarding the achievement of decarbonisation targets for buildings that undergo the step-by-step retrofitting approach. This model was implemented as a mixed-integer linear programming (MILP) code in Python using the Pyomo language [45–46] and Gurobi as the solver. Fig. 1 presents the code architecture, especially specifying the input data requested.

3.1.1. Objective function and constraints

The objective function defines the main target of the step-by-step optimisation: to maximise the net present value of the (cumulated) household income available for energy-related assets minus energy-related expenditures over a certain optimisation period. The retrofitting model is set from the homeowners' perspective and is based on three main premises: First, an economic premise that the homeowner allocates a regular part of her/his income and spends part of it for energy-related expenses (investment costs for retrofitting measures, running energy, and maintenance costs) – section 3.1.2 [47–48]. The second premise refers to the investment costs of a renovation measure. The investment costs consist of energy-related costs and usual costs. The former are the costs of generating energy efficiency improvements, while the latter are regular expenses (which usually occur as maintenance). The building materials' ageing processes were used as a variable to represent this phenomenon in the model – explained in section 3.1.3. The third premise refers to the residual value of the investment cost when the optimisation period is achieved, as explained in section 3.1.4.

$$\max NPV = \sum_{t}^{T} \frac{CF_t}{(1+r)^t} + \frac{L_T}{(1+r)^{tp}} \tag{1}$$

NPV, energy-related net present value [EUR]; CF, cash-flow of energy related balance; L, residual value of the retrofitting measures in year T; *r*, interest rate [%]; tp, depreciation time [a]; *T*, optimisation period [a].

The model has a constraint, which refers to the interdependency of performing the steps. Two possibilities were analysed:

1) **"Dependency"** means that a heating system replacement is foreseen in the model, but it can only happen after the other steps have been performed;
2) **"No dependency"** means that the step containing the heating system can be performed at any time, independently of the other steps.

The main reason for setting the constraint "with dependency" is that it would guarantee that the full load operation of the replaced the heating system. In real life, however, due to its shorter lifetime (usually about 25–30 years), the heating system is commonly replaced before other renovation measures are performed, working for many years oversized, and consequently, inefficiently.

3.1.2. Energy-related cash flow

The energy-related cash flow (CF) of the homeowner (assuming an owner-occupied building) in every year t is the cumulated allocated asset (A_t) (see also 3.1.2.1) minus the energy-related expenditures (IC, EC and OMC) (see also 3.1.2.2 to 3.1.2.4):

$$CF_t = A_t - IC_t - EC_t - OMC_t \tag{2}$$

CF, cash flow of energy-related balance [EUR]; A, cumulated allocated energy-related asset, in the time t [EUR]; IC, sum of investment cost, in the year t [EUR]; EC, annual running energy costs, in the time t [EUR/a]; OMC, annual running operation and maintenance costs, in the time t [EUR/a].

3.1.2.1. Cumulated and allocated energy-related assets and budget restriction.

The cumulated allocated asset (A_t) destined to energy-related issues in the year (t) is related to the household's income (INC), its share (s) and cumulated assets from the last period t-1 (A_{t-1}):

$$A_t = (INC_t{*}s) + A_{t-1} \tag{3}$$

A, cumulated allocated energy-related asset [EUR]; INC, household income [EUR]; s, allocation factor of total annual income on energy-related expenses [%];.

These cumulated assets in year t (A_t) represent the budget restriction that the household faces. In addition, the household may take up a loan. The amount of the loan that the bank is willing to provide is assumed to be proportional to the cumulated assets and represented by the variable l. Thus, the overall budget restriction in year t (B_t) may be written as:

$$B_t \geq IC_{,t} + EC_t + OMC_t \tag{4}$$

with $B_t = A_{t-1}{*}(1+l)$

B; budget restriction [B]; IC, investment cost of retrofitting measures [EUR]; EC, annual running energy costs [EUR/a]; OMC, annual running operation and maintenance costs [EUR/a]; l, loan [%].

3.1.2.2. Investment costs.

The investment costs (IC_i) for each retrofitting step (i) that has to be carried out: building envelope (external wall, window, floor, or roof)and active system (heating, cooling, domestic hot water), considering the energy-related investment cost ($ICer_{t,i}$), the maintenance investment cost ($ICman_{t,i}$), the probability of material's ageing process ($p_{t,i}$) (see 3.1.3) and a binary control variable ($x_{t,i}$), which indicates if the measure is performed in year t or not:

$$IC_i = \sum_t \left[(1 - p_{t,i}){*}ICman_{t,i} + ICer_{t,i} \right]{*}x_{t,i} \tag{5}$$

where, $x_{t,i} = 1$ or 0 and $p_{t,i} > 0.05$

IC, total investment costs [EUR]; ICer, energy-related investment costs, for each retrofittig step (i) [EUR]; ICman, maintenance investment cost , for each retrofitting step (i) [EUR]; x, binary variable (1 or 0) [-], if the step i is performed in the time t; p, ageing process probability of building material's or technical system of step i [-];

The assumption behind this equation is that if the probability that a renovation measure has to be carried out is close to 1, then, IC_{man} is not relevant for the investment decision because the step has to be carried out anyway.

3.1.2.3. Energy costs.

The running energy costs of the active system (i) at the time (t) are related to the final energy demand (fed) and the prices (pr) of the corresponding energy source[49]:

$$EC_t = \sum_i fed_{t,i}{*}pr_{t,i} \tag{6}$$

EC, energy costs [EUR/a]*; fed,* final energy demand [kWh/a]; *pr,* energy price [EUR/kWh].

If a retrofitting measure is carried out, the final energy demand is reduced and has to be recalculated. The energy savings achieved are presented by the factor f, which depends on the energy-related investment costs IC_{er}:

for,

$$\begin{aligned} x_t = 0, fed_{t+1} = fed_t \\ x_t = 1, fed_{t+1} = fed_t{*}f(IC_{er,i}) \end{aligned} \tag{7}$$

3.1.2.4. Operation and maintenance costs.

The operation and maintenance costs for the active systems (i) at the time (t) are related to investment costs (IC) and the operation and maintenance factor (f_{OMC}):

$$OMC_t = \sum_i IC_{t,i}{*}f_{OMC,i} \tag{8}$$

OMC, operation and maintenance costs [EUR/a]; *IC,* investment

Table 3
Cases studied building data, Source: iBRoad-project, 2019 [20].

ID	Country	Year of construction	Net floor area [m^2]	Year of heating system replacement	Heating System
1	PT	1937	74	1937	Electric heater
2	PL	1975	218	1975	Gas boiler
3	PL	1975	368	2004	Gas boiler
4	PL	1981	285	1981	Coal boiler
5	BG	1994	160	1999	Air heat pump

costs of active system [EUR]; f; operation and maintenance factor [%].

3.1.3. Material's ageing process probability

The probability (p) of retrofitting measures (i) at the time (t) is defined by the Weibull distribution of material's aging process [50,51]:

$$p_{t,i} = 1 - e^{-\left(\frac{t-t_{i,0}}{t_{i,L}-t_{i,0}}\right)^m}, where, t_0, m > 0 \tag{9}$$

p; probability of material's aging process*;* m*,* aging exponent *[-]; t_L,* technical lifetime [a]; t_O*,* period without failure [a]; *t,* time [a].

3.1.4. Residual value

The residual value (L) by the end of the optimisation period (T) of each retrofitting measures investment (IC,i) is related to the building material's and technical system lifetime ($t_{L,i}$), thedepreciation time (t_P) and the optimum time delivered by the model (top):

for,

$$\begin{aligned} t < t_{L,i}: \quad & L_T = IC_i * \frac{t_{L,i} - (tp + top_i)}{t_{L,i} * (1+r)^{tp}} \\ t \geq t_{L,i}: \quad & 0 \end{aligned} \tag{10}$$

L, residual value [EUR]; IC total investment costs, for each step i [EUR]; t_L, building material's and technical system lifetime for each step i [a]; *tp,* depreciation time [a]; top, optimum time defined by the optimisation model for each step i [a].

3.1.5. Final energy savings

The final energy savings (ES) is the relation between the status quo final energy demand (fed_sq) and the final energy demand (fed_i) achieved after the renovation step is performed:

$$ES_i = \frac{\text{fed}_{sq} - \text{fed}_\text{i}}{\text{fed}_{sq}} \tag{11}$$

ES, energy savings per step i [%]; final energy demand of the status quo [kWh/a]; final energy demand per step i [kWh/a].

3.1.6. Cumulated energy savings

The cumulated energy savings (CES) is the sum of all energy savings per step (ES_i) over the period (p):

$$CES = \sum_1^i ES_i * p_i \tag{12}$$

CES, cumulated energy savings [%a]; i, number of steps of the renovation roadmap. For single-step renovation, i = 1. In the present step-by-step model, i = 3; p, time period of step i, between its implementation and the next step [a].

3.2. Model assumptions and input data

Below, the model assumptions will be explained in more detail. Furthermore, the input data used for the calculations are provided in Table 3 and Table 4 (in chapter 4).

- **Renovation cycles:** the present model delivers the optimum timing for one renovation cycle, for the specified renovation period. This means that each step is performed a maximum of one time. The model decides if the step should be performed and when (what year) – called the optimum timing (top).
- **Retrofitting measures and their investment costs (IC):** defined in the Equation *(5)*. In the step-by-step approach, a step consists of one or more retrofitting measures (or a package of measures). In the present paper, the dedicated energy auditors defined the measures (and their combination) while developing the roadmaps within the EU H2020 iBRoad project, in three different countries Portugal, Bulgaria, and Poland.
- **Building material lifetime database (t_L):** included in the Equation (9) and Equation *(10)*. A database of the building material and heating technology lifetime was set based on the literature review [49] and [51]. Building materials of each building element have to be defined in the input data files, and the code automatically allocates its lifetime based on the database (also online accessible[1]).
- **Material ageing rate (m):** included in the Equation (9). It was assumed as 6.5, based on the literature [52] and [53].
- **Heating system technology:** both currently installed and foreseeing in the roadmap are specified (per building) in the Table 3 and Table 4. For the specified heating technologies (and their energy carrier), the model reads the energy carrier prices automatically from the database.
- **Energy prices and heating technology prices (EC):** included in the Equation *(6)*. Energy prices and price developmentas well as heating technology prices were determined based on the literature review. Mainly, different modelling scenarios were used [54–57] (also online accessible[2] or Appendix A)
- **Optimisation period (T):** An optimisation period of 30 years, from 2020 until 2050, was considered.
- **Depreciation time (tp):** the depreaciation time was considered 30 years.
- **Annually allocated energy-related asset (A):** An annual allocated income of 3,000 euro was considered for all cases, which cumulated over the 30 years of the optimisation period. This annual allocated income results from 10% (s) and 30,000 euro disposable income (INC). The disposable income assumption was based on a literature review of European's disposable income [59,64,65], and represents most European households. This assumption represents real-life conditions in that household income is not necessarily directly related to the building's gross floor area. For the sensitivity analysis, a worst-case scenario of 900 euro and a best case scenario of 6,000 euro annually were considered.
  Loan (l): The model allows the consideration of incentives and loans as input data. However, these were not considered in this study because they were not specified in the case studies.
- **Interest rate (r):** The model calculated with a conservative interest rate of 3%.
- **Number of steps (i):** The number of steps reflects how fast the planned energy savings are achieved: the higher the number of steps, the longer it would take to finish performing the whole renovation plan. This model was outlined to provide the calculations for a roadmap with three steps (i = 3). This is considered a plausible number of steps and is also used by the Land Salzburg (Austria) to provide step-by-step recommendations in the energy performance certificates (EPC). If other numbers of steps have to be considered, the model should be adjusted as well as the decision variables. Step 3 allocates the active system measure, if it is foreseen in the roadmap. With this solution, it was possible to study the two different constraints "dependency" or "no dependency," which impacts whether or not Step 3 is performed.

[1] Under the link: https://eeg.tuwien.ac.at/gitlab/ina/stepweise-opto

Table 4
Step-by-step roadmaps and model input data per step: building 1–5, Source: iBRoad-project, 2019 [18].

ID	Step	Measure/Package of measures	Primary energy demand [kWh/m^2]	Useful energy demand [kWh/m^2]	Carbon emission [kg/m^{2}a]	Investment cost [Euro]	Main energy source
1	**0**	**Status quo**	**600**	**327**	**100**		**electricity**
1	1	Thermal insulation on exterior walls - application on the inside with light coating; thermal insulation with sloped roof - application on the slopes on the resistant structure of the sloped roof; Replacement of existing frames with energy class A windows	249	99	36	14,500	electricity
1	2	Add a biomass boiler	51	112	7	3,000	wood
1	3	Installation of individual inclined solar thermal system	27	87	4	2,000	wood
2	**0**	**Status quo**	**474**	**427**	**86**		**natural gas**
2	1	Pipe insulation; Installation of a thermal solar system for domestic hot water	343	317	63	2,222	natural gas
2	2	External Wall insulation;Roof insulation; Substitution of the old doors	163	154	30	17,384	natural gas
2	3	Substitution of the old windows	134	127	25	9,160	natural gas
3	**0**	**Status quo**	**382**	**344**	**70**		**natural gas**
3	1	External Wall insulation;Substitution of the heating system by a condensing gas boiler; Add a thermal solar system	234	214	43	15,151	natural gas
3	2	Roof insulation	153	140	28	5,210	natural gas
3	3	Substitution of the old windows; Substitution of the old doors	123	113	23	10,536	natural gas
4	**0**	**Status quo**	**435**	**396**	**100**		**hard coal**
4	1	Substitution of the old doors	431	392	99	2,597	hard coal
4	2	Insulation external walls	235	214	99	29,616	hard coal
4	3	Insulation of ceiling	185	168	56	43,257	hard coal
5	**0**	**Status quo**	**504**	**168**	**100**		**electricity**
5	1	External Wall insulation; Roof Insulation; Change glazing with energy saving glazing	300	100	13	9,537	electricity
5	2	Installation of a thermal solar system for domestic hot water	227	92	12	2,550	electricity
5	3	Substitution of the heating system by a heating pump	176	59	8	6,120	electricity

4. Case study

During the EU H2020 iBRoad project testing phase (the project also described in section 2.1), energy auditors developed individual step-by-step roadmaps for several real buildings. The number of steps per roadmap, as well as the packages of measures per step, were defined by the energy auditors. A pre-analysis of developed roadmaps was performed to five selected cases. The cases were selected according to the consistency of the information and the number of steps foreseen by the auditor (for the model it should be three). Using the data developed from the project allows validating the model with real-life values and not theoretical ones. Table 3 below presents general building information including building ID, country, year of construction, net floor area, and year of heating system replacement. Table 4 provides more detailed information about the individual building roadmaps per step, including the package of measures per step, primary energy, useful energy, total investment, carbon emission, and energy carrier. These data were used as input data to assess and validate the model outlined.

The roadmaps developed (Table 4) show a variety of solutions provided by the energy auditors. Under other aspects, it is to highlight that not all roadmaps foresee the heating system replacement, which indicates that decarbonisation targets were not the focus of some roadmaps. Another relevant observation is that in Step 2 for Building 1, negative final energy saving is observed. This is probably because a less efficient biomass boiler is suggested, which is less CO_2 intensive. The data from both Table 3 and Table 4 were prepared and adapted to the code structure (Fig. 1) serving as input data to the retrofitting optimisation model.

5. Results

The sequence from the iBRoad roadmaps were compared with the optimisation model to validate the model. Section 5.1 presents the results. Section 5.2 presents the optimum timing and compares the results of two different constraints variants that represents the interdependency of the steps. Section 5.3 provides a comparison between both single-step and step-by-step approaches. And, and Section 5.4 presents the results of the net present value.

5.1. Comparison with real-life roadmaps

Fig. 2 shows the sequence of the steps defined by the energy auditors (iBRoad roadmaps), and the constraint variant “variants (“dependency” and “no dependency”.”) for five buildings cases. In the “dependency” variant, the constraint forces the steps to be performed in the given sequence. The last step (Step 3) includes the active system (i.e. heating system). “No dependency” means that the model decides independently when and whether or not to undergo each step.

The sequences above show that the model implements the constraints correctly. In both variants, the model can decide if the step is performed (or not). If possible, more than one-step can be performed at the same time. In the constraint variant “nono dependency”, the model performs Steps 1 and 2 after each other or together. Step 3 is the last one to be performed. Contrastingly, the constraint variant “dependency” allow dependency” allows the model to decide freely about the sequence.

The present step-by-step retrofitting model goes beyond the energy auditor’s roadmap. Besides the step sequence, the present model calculates the optimum timing when the steps should be performed, while the iBRoad roadmaps only indicate the step sequence. The results of the optimum timing delivered by the model, for both variants, are discussed below.

5.2. Comparison between different constraints

Table 5 shows the optimum timing, and consequently, the optimum year that each renovation step should be performed. This answers RQ1 and shows that the model is able to calculate the timing indications for the step-by-step approach for the maximised net present value. Regarding RQ2, the same table presents a comparison between the results generated by using two different constraints: “dependency” and “no dependency.” ”Dependency” suggests dependency on the sequence

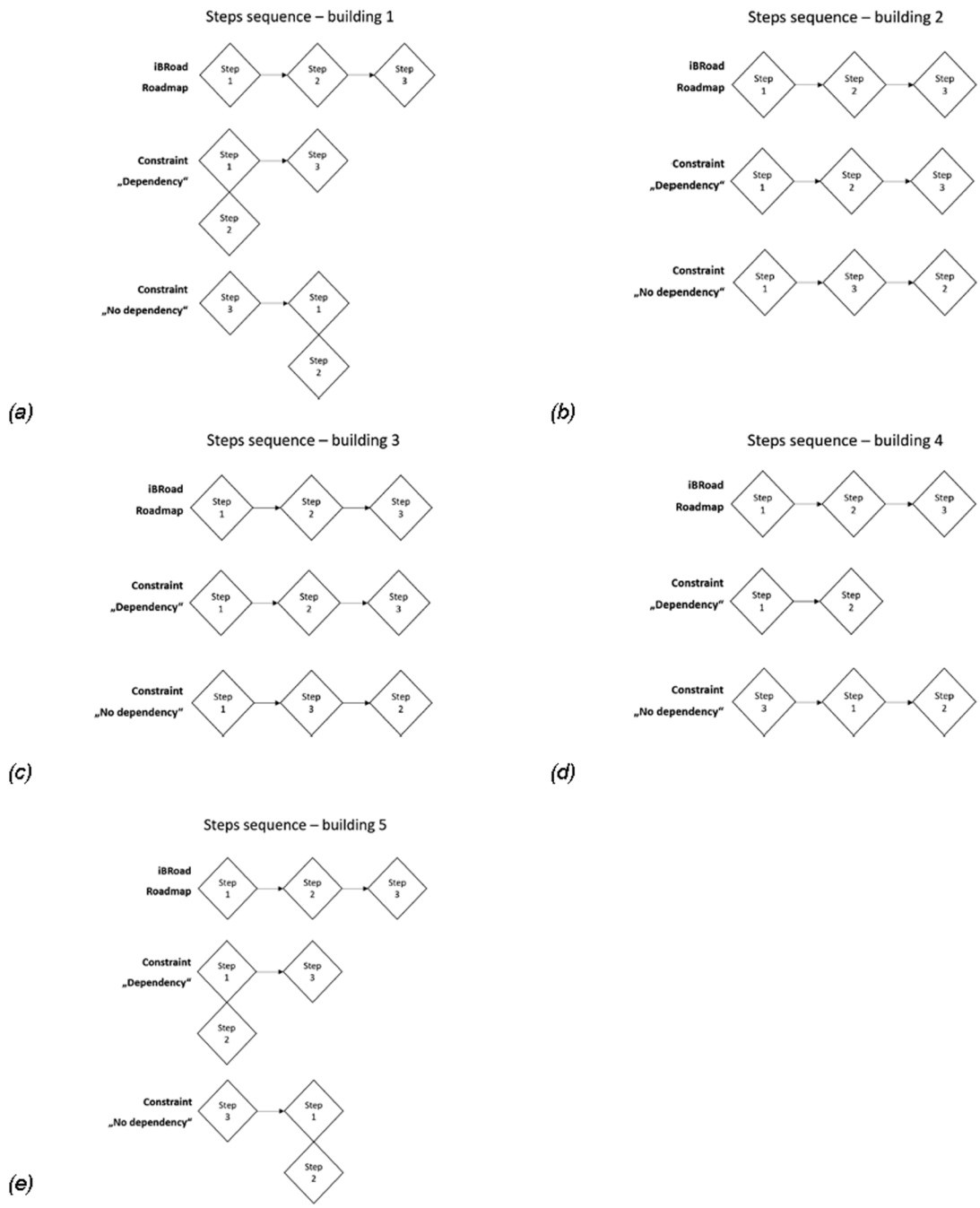


Fig. 2. Steps sequence - building 1 to 5. The steps sequence defined in the iBRoad roadmaps, and in the optimisation model using both constraint variants “dependency” and “no dependency”.

when performing the steps (as explained above). Forcing the model to perform Step 3 as the last step allows the right dimension of the new heating systems (adapted to all envelope measures foreseen in the roadmap and allocated to Step 1 and 2). “No dependency” means that the model may decide independently when and whether or not to undergo this last step. However, if Step 3 is performed after Step 1 (or Step 2), it may result in the heating system operating oversized for an extended period of time.

From the table, it can also be observed that all three steps were performed in both constraints for all buildings and except for Building 4. For Building 4, Step 3 was not performed in the variant “dependency”, due to the combination of high costs and the limited optimisation time of 30 years. In this case, as Step 2 was performed in 2047, and the optimisation period goes until 2050, more time would be necessary to cumulate the asset to cover Step 3 costs. In general, it can be observed that in the variant “dependency”, Step 3 (which includes heating system replacement in the roadmaps that foresee this measure), was performed later than in the variant “no dependency”. The total period of a renovation roadmap (the period between the first and the last step) for all buildings except Building 4, varied between 1 and 14 years (variant with “dependency”) and 2 to 11 years (variant with “no dependency”). Building 4 had a calculated roadmap period of 26 years and 17 years, for the variants “dependency” and “no dependency”, respectively.

Beyond the fact that the constraint “dependency” delays (and might even prevent) a step, it is crucial to analyse the cumulated energy savings over the considered period for both variants. The graphs 1 to 5 below show a comparison of the cumulated energy savings (for the period between 2020 and 2050) for all five test cases and for each

Table 5
Optimum optimisation yeary when each step should be peformed - two constraint variants that represent the interdependency of the steps "dependency" and "no dependency."

ID	Renovation step	Dependency between steps	No depedency between steps
1	Start	2020	2020
	Step 1	2025	2025
	Step 2	2025	2025
	Step 3	2026	2021
2	Start	2020	2020
	Step 1	2021	2021
	Step 2	2032	2032
	Step 3	2035	2024
3	Start	2020	2020
	Step 1	2022	2022
	Step 2	2027	2028
	Step 3	2033	2027
4	Start	2020	2020
	Step 1	2021	2031
	Step 2	2047	2047
	Step 3	–	2030
5	Start	2020	2020
	Step 1	2024	2024
	Step 2	2024	2024
	Step 3	2027	2022

constraint variant "dependency" and "no dependency". The cumulated energy savings corresponds to the area below the graph lines (blue and red, respectively). The grey area indicates the difference between the cumulated energy savings between both variants. The arrows indicate which step is being performed: (See Graph 1)

- **Building 1:** The negative final energy demand savings happens due to the replacement of the heating system by a lower efficiency biomass boiler. The cumulated energy savings are very similar in both cases. For the variant with "no dependency", the heating system would operate oversized for 29 years, while in the variant "dependency" for 6 years;
- **Building 2:** For this building case, the variant with "no dependency" presents higher cumulated energy savings. For the variant with "no dependency", the heating system would operate oversized for 26 years, while in the variant "dependency" for 15 years;
- **Building 3:** For this building case, the variant with "no dependency" presents slightly higher cumulated energy savings. For the variant with "no dependency", the heating system would operate oversized for 29 years, as the heating system would be replaced between Step 1 and Step 2. While in the variant "dependency" the heating system would operate oversized for 13 years;
- **Building 4:** For this building case, the variant with "no dependency" presents significantly higher cumulated savings. This happens because Step 2 has very high costs, which hinders the last step from being performed during the optimisation period. For the variant with "no dependency", the heating system would operate oversized for 29 years, as the heating system would be replaced between Step 1 and Step 2;
- **Building 5:** For this building case, the variant with "no dependency" presents higher cumulated savings. For the variant with "no dependency", the heating system would be oversized for 28 years, while in the variant "dependency" for 7 years.

In general, it was observed that the constraint "dependency" enables the heating system to operate for a shorter time as an oversized system, but the cumulated energy savings over the period are then lower.

This model does not consider that the heating system in part-load has a lower efficiency; however, it is important to economically quantify this trade-off between energy savings and the heating system's operation. The next steps of the present study will include implementing a heating load capacity factor. For the results presented in the next section, it was chosen to use the constraint "no dependency" as it better illustrates real life's praxis where replacing the heating system does not necessarily happen as a last retrofitting step. Actually, the contrary is observed in real-life praxis: due to its shorter material lifetime and lower investment costs, heating systems are not replaced after improving a building's envelope energy efficiency.

5.3. Comparison with single-step

The results presented in this analysis were calculated using the constraint "no dependency". In this section, the cumulated energy savings of both step-by-step and single-step approaches are compared and presented in Graph 2 below. To illustrate the difference between both approaches, the single-step timing was first defined. For that, a simplified assumption is made: the number of years that the homeowner needs to achieve the investment costs (of the whole roadmap in Table 4) by annually allocating the energy-related asset (A) (section 3.2).

The graphs above show the cumulated energy savings per renovation approach (single-step and step-by-step) for every each of the five buildings. The grey areas show the cumulated energy savings difference. In all five cases, the step-by-step approach present higher cumulated energy savings than the single-step. Building 4 presents a very high difference (75%). The step-by-step presents 11–22% higher cumulated energy savings in the other buildings, as shown in Table 6.

In general, the single-step approach provides faster achievement of energy savings. Ideally, retrofits should be performed as early as possible to guarantee high cumulated energy savings. However, in real life, due to homeowner's financial barriers, retrofits may be postponed or delayed. With the step-by-step retrofitting, on the other hand, the energy savings increase gradually and are performed according to homeowner's affordability. In real-life, the chosen renovation approach is directly linked to the homeowner's budget restriction. The present results reinforce the importance of including accurate homeowner's budget restrictions in building retrofitting models.

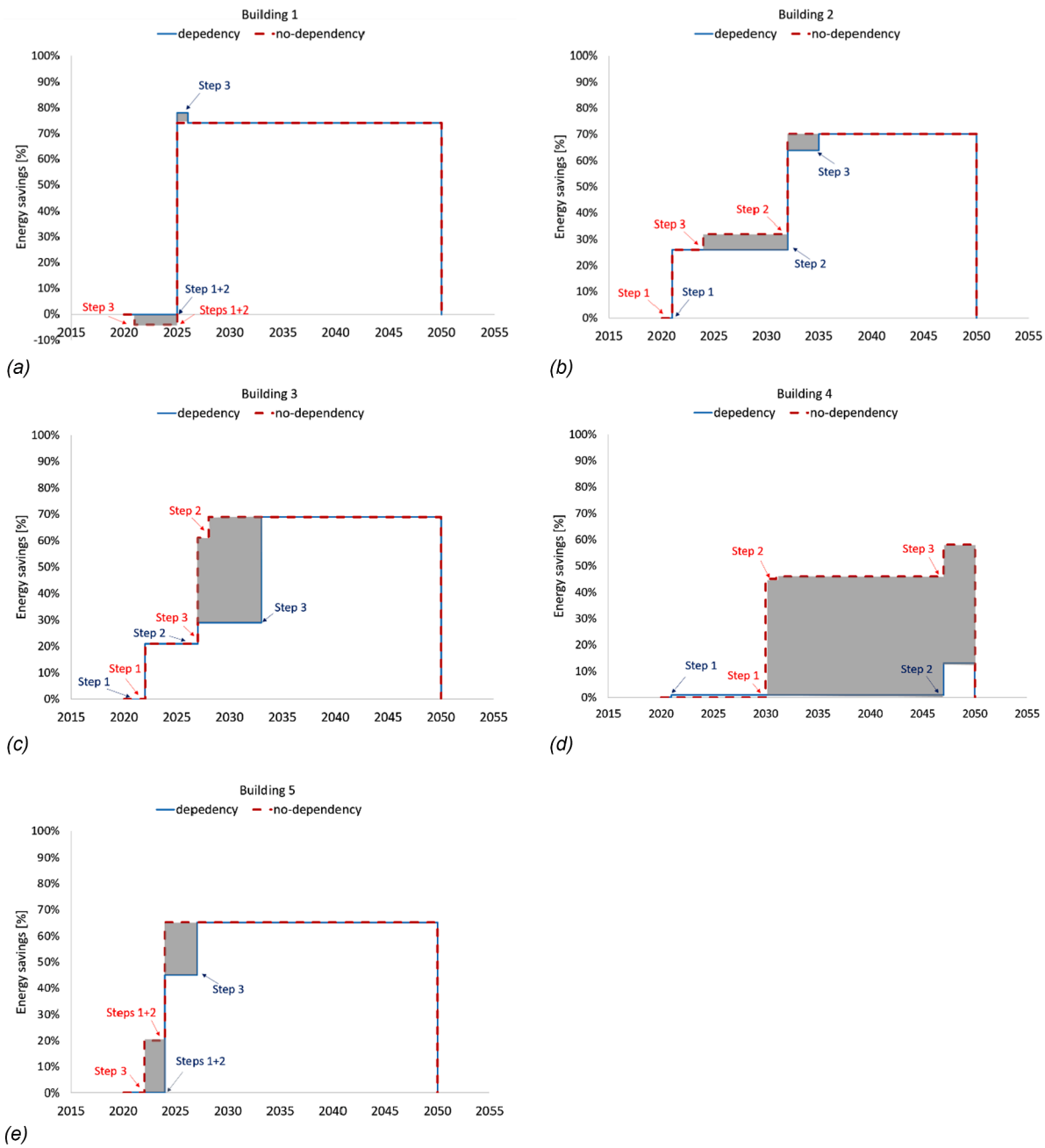
5.4. Analysis of the net present value

The results presented in this analysis were calculated using the constraint "no dependency", as previously explained.

The present analysis consists of an in-depth examination of each household's cash flow by calculating the maximised net present value according to equations (1) and (2). In these equations, energy-related expenditures (investments, cost of retrofitting, energy cost, and operation and maintenance costs) and the investment's residual value are subtracted from the household's cumulated assets for energy-related expenditures. Graph 2 shows the maximised net present value of these five indicators for each of the five buildings as well as the "net" net present value that results from their subtraction:

In general, the graph shows that the relation between cumulated assets, total investment, and energy expenditures is the most relevant in determining the net value. Therefore, Chapter 6 presents a sensitivity analysis of both parameters. Below, is the analysis for each building:

- **Building 1** has a positive net value due to its lower net present value of total investment and energy expenditure.
- **Building 2 and Building 3** have similar results. However, Building 3 has a higher net present value of energy expenditures, which results in a lower net value than Building 2;
- **Building 4** has a high net present value of investment costs and high residual values. The high step costs (see Table 4) influence a "later" optimum timing for performing the steps, which consequently generates higher residual values;
- **Building 5** has a "net" net present value close to zero. The main difference between Building 1 and Building 5 is the net present value of energy expenditure costs.



Graph 1. Cumulated energy savings comparison – buildings 01 to 05. The graphs show a comparison between both constraint variants: "dependency" (blue line) and "no dependency" (red line). The arrows show which step is performed. The grey areas indicate the difference of the cumulated energy savings between both variants.

6. Sensitivity analyses

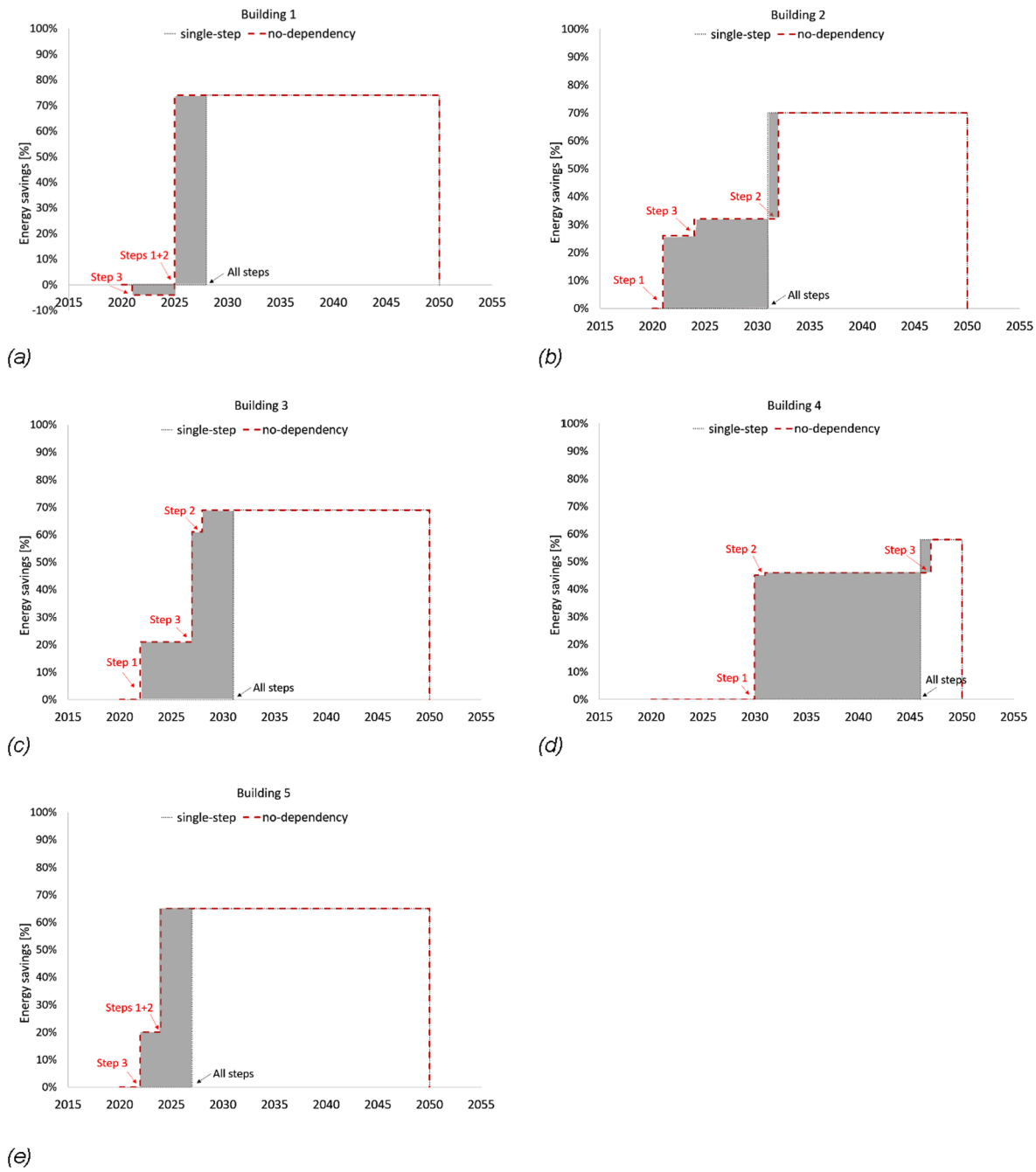
This chapter investigates the sensitivity of the model when varying the parameters budget restriction (Section 6.1), energy prices (Section 6.2)), and renovation costs (6.3).Budget restriction

Table 7 presents the optimum year for three different annual incomes (900; 3,000; and 6,000 euro). It presents a sensitivity analysis of how the calculated optimum timing may change based on the homeowner's budget restriction.

This table answers RQ3, as it shows that a lower budget may delay the optimum timing. Between the 3,000 euro and 6,000 euro budget, the difference is not that significant (although the budget is two times higher) due to the net present value of total investments. As shown in Equation (5), the share of usual maintenance investments and energy-related investments define the total investment. This equation also shows that the material's lifetime, represented by the probability of the material's ageing process, determines the share of regular maintenance investment costs: over time, as the material's end of life nears, the total energy-related investments reduce. Consequently, very early investments (although contingent on available budget) might represent a higher total energy-related investment. Furthermore, a high budget restriction does not necessarily result in earlier optimum timing.

6.1. Energy prices

Graph 3 shows the net present value by considering higher energy prices due to increased CO_2 taxes. The energy prices did not influence the optimum timing; however, the net values were negatively affected in



Graph 2. Cumulated energy savings comparison – buildings 1 to 5. The graphs show a comparison between both: step-by-step – variant "no dependency" (red line) and single-step (black line). The arrows show which step is performed. The grey areas indicate the difference between the cumulated energy savings between both variants.

Table 6
Cumulated energy savings per renovation approach (single-step and step-by-step) - building 1 to 5.

ID	Cumulated energy savings [%a] Single-step	Step-by-step
1	16.3	18.3
2	13.3	15.9
3	13.1	16.8
4	2.3	9.6
5	15.0	17.3

the buildings in which the individual renovation roadmap did not foresee the replacement of the fossil fuel heating system.

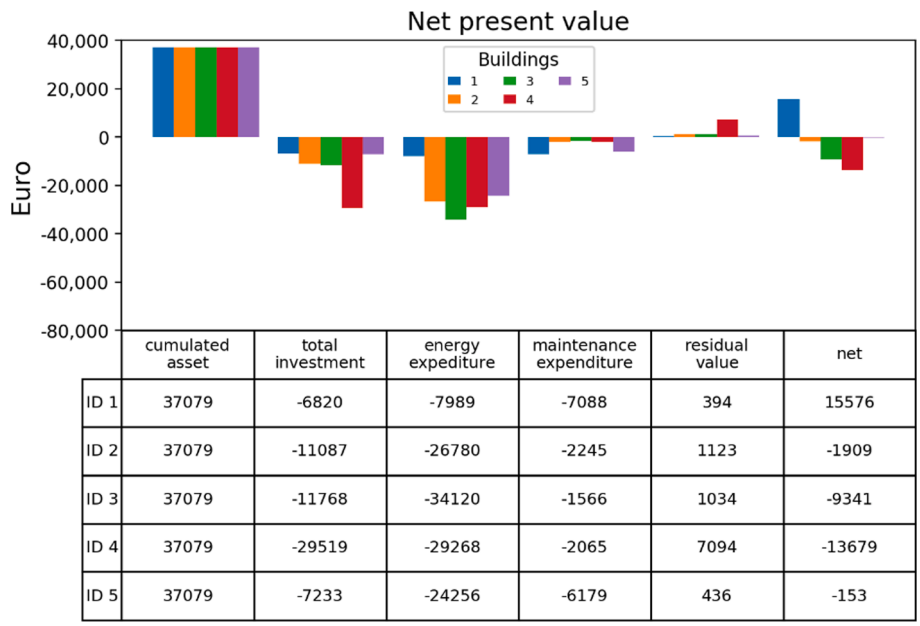
Building 1's energy expenditure costs do not increase significantly because of the energy carrier. Unlike the other buildings, the individual building roadmap for Building 1 was the only one that foresaw an energy carrier replacement from electricity (with high renewables) to biomass. (See Graph 4)

6.2. Renovation costs

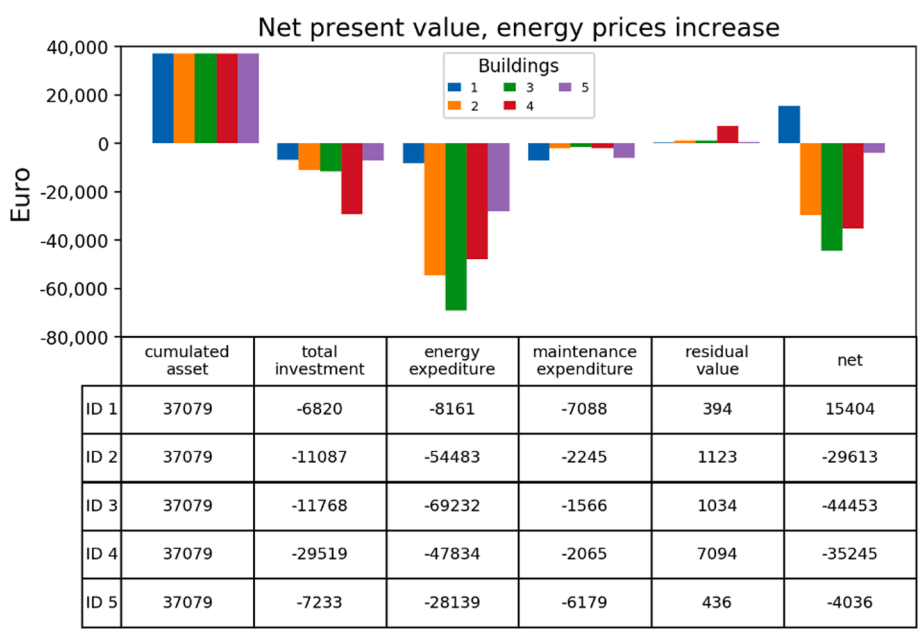
Table 8 presents a sensitivity analysis on how the calculated optimum timing may change in two renovation costs scenarios: constant

Table 7
Comparison of the optimum year resulting from different annually allocated income share: 900, 3,000 and 6,000 euro.

	Budget: 900			Budget: 3,000			Budget: 6,000		
ID	Step 1	Step 2	Step 3	Step 1	Step 2	Step 3	Step 1	Step 2	Step 3
1	2034	2036	2023	2025	2025	2021	2023	2024	2021
2	2023	2050	2032	2021	2032	2024	2021	2027	2023
3	2038	2041	2037	2022	2028	2027	2022	2026	2025
4	2023	–	–	2031	2047	2030	2021	2037	2027
5	2031	2034	2027	2024	2024	2022	2024	2024	2022



Graph 3. Net present value of building's cash-flow - building 1 to 5.



Graph 4. Net present value of building's cash-flow, considering higher energy price scenario (due to CO_2 taxes) - building 1 to 5.

renovation costs and annual renovation cost deacrease of 0.5%. The results show that the model is sensitive to these changes by anticipating (about 1 to 2 years) some steps' performance due to the lower costs.

This analysis considers that the cost reduction percentage is equal in all steps. For this reason, there was no change in the sequence of the steps. However, the model might change the sequence if there is a significant renovation cost modification in one of the steps. For example, one such modification could be if the government grants a technology subsidy to support a specific technology or building material.

Table 8
Comparison of the optimum year resulting from the two variants: constant renovation costs and decreasing renovation costs.

	Constant renovation costs			Decreasing renovation costs		
ID	Step 1	Step 2	Step 3	Step 1	Step 2	Step 3
1	2025	2025	2021	2024	2024	2021
2	2021	2032	2024	2021	2031	2024
3	2022	2028	2027	2022	2028	2027
4	2031	2047	2030	2031	2045	2030
5	2024	2024	2022	2023	2024	2022

7. Discussion and next steps

Until recently, the policy instruments have focused on the single-step building retrofitting approach for two main reasons. Firstly, such an approach allows fast CO_2 emission reduction once the retrofit takes place. Secondly, the risk is lower in committing technical mistakes that affect future activities when the retrofit is performed at once. This changed in 2018 with the recast of the Energy Performance of Buildings Directive (EPBD) 2018/844/EU and the introduction of a building renovation passport (and thus the explicit consideration of step-by-step retrofitting). Although expert opinions still diverge regarding this retrofitting approach [60], studies have already shown empirical evidence that it is commonly performed in many real-life scenarios. Therefore, developing more studies about the step-by-step renovation approach, its technical burdens on the implementation, understanding homeowner's conditions to perform it, and its effects on the achievement of EU's decarbonisation targets will help enrich the actual state of knowledge.

The literature review did not identify any model covering the optimum timing of step-by-step retrofitting, and that is the main contribution of the present paper to the existing literature. The present paper sets up a framework for a step-by-step retrofitting optimisation model that considers three different aspects: budget restrictions (based on households' allocated income for energy-related expenditures and, if available, loans or incentives); building material ageing processes; and interdependency between the retrofitting steps. The model maximises the net present value of a household's energy-related cash flow. The model's primary goal is to calculate the optimum timing when each step (or package of renovation measures) should be performed.

Based on the results, it can be concluded that in low-income households living in less energy efficient single-family houses, the retrofitting steps would – under consideration of maximising NPV – be performed later, if no loans or appropriated countermeasures were available. Beyond that, the model's optimum timing gives a more concrete time horizon perspective when the national building stock decarbonisation targets set for 2050 can be met. This was more evident in building 4, for which the comparison of two possible constraints showed that either step 3 would not be performed or would be performed very late; consequently, a better energy performance would not be achieved.

Based on the comparison of the different constraints, two relevant topics were discussed: the appropriate metrics to assess energy savings and the time of heating system replacement. The cumulated energy savings seems to be the most appropriate indicator to assess energy savings from retrofitting activities, not the "pure" energy savings that is the commonly used indicator, because the cumulated energy savings calculation also represents the time dimension when the savings are achieved. When it comes to the right timing for replacing the heating system, ideally, heating systems should work at full load capacity because when only at partial load they are less energy efficient which affects the energy costs. Because of that, this paper compared two different constraints to analyse the effects of the interdependency of the steps: "dependency" and "no dependency". In the "dependency" variant, the model indicates that the heating system replacement should be performed as the last step. In the "no dependency" variant, no predefined condition regarding the sequence is foreseen.

Also, a comparison between the single-step and the step-by-step approach was provided. To define the right timing of the single-step approach, a simplified assumption was made: the right single-step timing is necessary for homeowners to accumulate the total investment based on the annually allocated energy-related asset. The total investment varied according to the building and was specified in the iBRoad roadmaps. The results showed that the step-by-step approach presented higher cumulated energy savings in all buildings for the considered scenario. However, if government subsidies are available, this may change. Also, the single-step approach is preferable if the retrofitting is performed as soon as possible.

The sensitivity analyses showed that the model is quite sensitive to allocated income as a relevant decision variable for defining the optimum timing. Moreover, a higher budget restriction does not necessarily mean earlier optimum timing. A variation on the energy prices did not directly affect the optimum timing; however, it affected the household's energy-related cash flow. Finally, the renovation cost decrease over the optimisation period generated an anticipation of the steps, favourable in terms of cumulated energy savings. Due to the equally distributed cost reduction, no change in the step sequence was observed. However, unequal investment cost change between the steps may affect the sequence in which they are performed.

The model can be applied to different countries, and the input-data can be country-specific defined. Therefore, this universal model can be used in the future to address cross-country comparisons. However, one limitation of the model is that there is no automatic interface with other software tools to help calculate the energy demand and costs per step. This functionality could save time and prevent mistakes during data input. Also, the results are based on the static energy price scenarios, previously defined in the database. Here, further implementation could provide a dynamic actualisation of energy prices. Finally, not implementing an over-sizing factor (which would correct the heating system's efficiency) is considered to be a relevant limitation of the model.

Two different target groups could profit from the present study: energy auditors and public authorities. When implemented, especially considering more implementation specifications, such a model can serve as a support tool to energy auditors by automatically definedefining the optimum timing of each step. Public authorities could profit from this model's results as they help increase the understanding of how fast the EU's decarbonisation targets set for 2050 can be achieved, especially considering a building's techno-economic characteristics. The next steps include further developing the model and applying it to more buildings, specifically various other building types.

8. Conclusions

This paper sets up a mixed-integer linear programming optimisation model for a step-by-step retrofitting approach. The step-by-step retrofitting optimisation model builds on techno and economic parameters. The main objective is to calculate the optimum timing when each step (or package of renovation measures) should be performed, by maximising the net present value of a household's energy-related cash flow. The model was tested with five real-life cases provided by the EU H2020 iBRoad project, and it successfully delivered reasonable step-by-step optimum timing indications.

Two constraint variants which represent the interdependency between the retrofitting steps were compared. Based on the comparison between these variants, two relevant topics were discussed: the appropriate metrics to assess energy savings and the sequence of performing the steps. The cumulated energy savings seems to be the most appropriate metric to assess energy savings because it also represents the time dimension when the savings are achieved. When comparing the step-by-step with the single-step approach, the step-by-step presented 11–22% higher cumulated energy savings. The results showed that the adequate constraint is the one which allows the model to freely decide about the step sequence and is not forced to replace the heating system last. This situation is closer to real-life renovation activities where

homeownerowners often change the heating system before performing other envelope measures. For most cases, the model calculated a total period of a renovation roadmap (the period between the first and the last step) between 1 and 14 years (variant with "dependency") and 2 to 11 years (variant with "no dependency"). Public authorities could profit from this model's results as they help increase the understanding of the time perspective on how fast decarbonisation targets set for 2050 can be achieved.

The literature review could not identify any step-by-step retrofitting optimisation model, which is the main contribution of this paper. With that, we prepare the ground for future studies that could further explore the following topics:

- Model analysis: Future studies could extend the current model's analysis to other building typologies (multi-family houses and non-residential buildings) while cross-cutting these typologies with more specific homeowner affordability profiles. A more detailed techno-economic classification of the building stock could obtain more accurate model results, including country-specific analysis or comparisons between national building stock decarbonisation trends. This work should also include a deeper analysis about the number of optimal solutions for the same building. Other possible model analysis refer to quantifying the economic effects of interdependency of steps, under the consideration of full and partial load operation.
- Renovation data: Although some studies have shown evidence of step-by-step renovation being broadly practised in real-life, there is still a considerable potential to be explored. Longitudinal data collection of real-life renovation activities and energy auditing advice (including developed renovation roadmaps) would improve model validation.
- Economic parameters: Various step-by-step decarbonisation scenarios can be further explored by considering the variation of economic parameters: energy and CO_2-emission price forecasts, interest rate forecasts, and building material and technology price variations, technology efficiency forecasts and the increased share of renewable energies in the electricity-mix (including energy production decarbonisation). An enhanced understanding of this topic could contribute to policy, financing, and subsidy schemes design, with the primary goal of stimulating renovation activities on the building stock.

CRediT authorship contribution statement

Iná Maia: Concept, Methodology, Visualization, Model implementation, Programming, Validation, Analysis, Input data verification, Writing, Editing. **Lukas Kranzl:** Concept, Methodology, Analysis, Writing, Reviewing, Supervision. **Andreas Müller:** Concept, Methodology, Model implementation, Analysis, Reviewing

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A:. Input data

The model requires following input data:

- Descripton of model's variable: Section 3.1 (Equations) and Section 3.2 (Input Variables and assumptions).
- Building related input data: Table 3 and Table 4, sources [18–19].
- Energy prices and assumpted forecastes, sources [54–57]:

Energy carrier	Price [EUR/MWh]	Forecast
Electricity	155	+1.5%/year
Gas boiler	13	+1%/year
Coal boiler	14	+2.1/year
Biomass	55	+1.2%/year
CO_2	20	+3%/year

- Building material and heating technology lifetime, sources [49 51]:

Building material / Heating system technology	Lifetime
Windows	30
Cement external wall	100
Gas and coal boiler	30
Sloped roof	60
XPS insulation material	30
Heat pump	20
Electric heater	25

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