

# Defining a framework to apply retrofitting optimisation models for long-term and step-by-step renovation approaches

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Abstract. The recast of Energy Performance of Buildings Directive (EPBD) 2018/844/EU introduced in the article 19a the possibility of building renovation passports which provide a long-term and step-by-step deep renovation roadmap for a specific building. Preliminary results showed that optimisation models for deep renovation of existing building almost exclusively optimise single stage retrofitting. Different from the single stage approach, in the step-by-step approach the retrofitting measures are not performed at the same time. In the present study, we aim to understand how the methodological approach of optimisation models for single stage retrofitting can be adapted to a step-by-step renovation concept. For this, first, the existing optimisation models were compared in terms of integration with external tools for energy demand calculation, definition of the renovation measures, objective function, and the question to which extent they consider long-term dynamic aspects of step-wise retrofitting optimisation over several years or even decades. Second, after identifying possible obstacles for adapting existing optimisation approaches towards step-by-step renovation, a framework for a step by step renovation optimisation model was outlined. The framework defines how the single stage retrofitting measures could be broken down in different renovation steps over a period of several years or even decades and which criteria should determine the time-wise prioritisation of the retrofitting measures. With this approach, we prepare the ground for the development of innovative tools, supporting the provision of individual renovation roadmaps. Next steps of the present study are testing and improving the outlined optimisation approach, as well as, extending the results to a building stock scale. By that, we aim to develop a method for analysing possible impacts of step-by-step renovation measures on achieving building stock's decarbonisation targets.

# 1. Introduction

The building sector has been identified as one of the key sectors for achieving the energy and climate policy targets of the EU, as buildings are responsible for 40% of energy consumption and 36% of  $CO_2$  emissions in the EU [1]. Although huge efforts have been made to reduce the energy demand of buildings, recent statists data about final energy consumption in households [2] and share of final energy consumption per fuel [3] have shown that there is still a long pathway to achieve the EU-targets. Therefore, is it necessary to find alternative deep renovation concepts for the building stock decarbonisation.

The EPBD recast 2018/844/EU introduced in the article 19a the possibility of building renovation passports, which provide a long-term and step-by-step deep renovation roadmap for a specific building. The step-by-step deep renovation roadmap is at its core a home-improvement long-term plan, which

considers the occupants' needs and specific situations and avoids the risk of lock-in effects, if future renovation measures are not considered in current activities. This document guide and help building owners through the renovation process, therefore dealing as an instrument to overcome barriers, as lack of acceptance. The building renovation passport is definitely an important instrument at EU level, to support deep renovation of existing buildings and bridge the gap between real renovation processes and the EU-targets for building stock decarbonisation.

In the literature, there is no consensus that deep renovation can also be achieved by a sequence of step-by-step renovation measures, which indicates that in fact, "deep renovation" is not necessarily restricted to single stage renovation. Nevertheless, creating more comprehensive modelling for this alternative retrofitting concept could help on accelerating the decarbonisation of the building stock due to suitable and right timing measures. In Europe, there are already some demonstration projects, which focus on the key concept of building passports, as the iBRoad EU-funded project, which works on eliminating the barriers between house owners and building energy performance, by developing building passport and step-by-step long-term deep renovation planning tool for single-family houses. Also, taking into consideration that in real life, the most retrofits activities are performed step-by-step [4], the main goal of the present paper is to outline a framework for the step-by-step renovation by adapting optimisation models for single stage retrofitting, and preparing the ground for the development of innovative tools, supporting the provision of individual renovation roadmaps.

# 2. Outlining a framework for step-by-step optimisation

#### Literature review

A retrofitting optimisation model aims at calculating the optimum solution of retrofitting measures' combination. The optimal retrofit strategy may include ecological (i.e. energy savings, CO<sub>2</sub> emissions, environmental impacts) and economic (i.e. net present value, investment cost, payback time, life cycle costs) objectives and/or restrictions. Many studies have presented different methods for selecting this most suitable solution, differing according to the targeted benefits, which are represented by the objective function. Therefore, the main objective of the literature review is to compare several models and to prepare the ground for outlining a framework for step-by-step optimization modelling. The models are compared in terms of integration with external tools and database, definition of the renovation measures and, methodological approach and aspects of time wise dynamic retrofitting over several years or even decades.

Most recently, Jafari et al. [5] reviewed at least sixteen literatures about energy efficiency decisionmaking, including not only multi-objective optimisation, but also other methods like multi-criteria, techno-economic evaluation method and others. The same authors present an optimisation framework to minimize the future cost (life cycle cost minus initial investment costs) of a building. 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 goes beyond building envelope (ceilings, walls, attic insulation), including load reduction measures (heating and cooling), controlling measures (ie. programmable thermostat) and renewables option (i.e. solar thermal and solar electricity).

Pombo et al. [6] 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 set of renovation measures chosen aimed at reducing space heating and cooling demand by insulating roof and façade, changing the windows and installing a heat recovery system. Asadi et al.[7] developed a model to assist stakeholders in the definition of measures aiming at minimizing the energy needs for heating, cooling and domestic hot water, and maximizing the investment costs. As set of retrofit actions, the authors considered window replacement, external wall and roof insulation and solar collector type. Wang et al.[8] proposed a life cycle cost approach, which aimed at maximizing energy savings and net present value while minimizing the initial costs. The chosen measures were lighting facilities, heat pumps, chiller, control systems and other devices, with focus on

reducing the electricity energy demand. Murray et al. [9] coupled a degree-days simulation with a generic optimisation procedure algorithms and compared both implemented and calculated retrofit solutions. This study aimed at minimizing the energy cost and carbon emissions post-retrofit, under the consideration of a payback period of maximum 5 years and capital investment. The adjustable parameter set were U-value from Attic, external walls and windows, boiler type and infiltration rate.

Table 1-summarises the studies presented above, its methods, main objective functions and chosen measures.

Refe- rence	Titel	Objective Functions Optimised	Benefits							Time step of	Energy
			Energy consumption	Retroffing measures	Energy cost	Retrofittig cost	Building material charactheristic	Maintenance cost	Thermal comfort	the measures	performance method
[9]	Optimization for Building energy retrofits decision making	Minimizes the total life cost Maximizes home owners economic benefits (optimum retrofit benefit) Budget restriction	x	x	x (natural gas, and electricity)	x		x		Single-stage	eQUEST
[11]	Multi objective optimatisation for building retrofit	Minimizes retrofit costs Maximizes energy savings	x	x		x				Single-stage	Simple thermal model – building code based (RCCTE - Portuguese), based on thee ISO 13790
[18]	Sustainable retrofits under uncertainities	No				x	x			Single-stage vrs multi- stage	No
[12]	Multi-objective optimization model for the life-cycle cost analysisand retrofitting planning of buildings	Maximizes energy saving Maximizes the discount pay back period Minimizes initial costs	x	x	x (electricity)	x	x	x		Single-stage	Unknown
[19]	A new methodology for investigating the cost- optimality of energy retrofitting a building category	Bottow up approach	x	x	x	x			x	Single stage	Energy Plus
[10]	Sustainability assessment of energy saving measures: A multi-riteria approach for residential buildings retrofitting—A case study of the Spanish housing stock	Minimum investment cost Maximum life cycle savings	x	x		x	x			Single stage	Energy Plus and DesignBuilder
[13]	Multi-variable optimization of thermal energy efficiency retrofitting ofbuildings using static modelling and genetic algorithms - A case study	Minimum energy cost Minimum carbon emission Maximum simple pay back time	x	x	x	x				Single stage	CIBSE Guide TM41, Degree Days

Table 1: Summary State of the Art

In the literature review some differences between the studies were observed, as for example the energy performance calculation method. While some authors used simplified calculation procedures, others used more complex dynamic simulation programs. On the other hand, all methods have in common not presenting any indication about the timing, when the retrofit measures are performed. This leads to the conclusion, that they do not cover the dynamic time wise aspect by considering that retrofitting measures are applied at the same time, so called single stage retrofitting.

Different from the single stage approach, in the step-by-step approach retrofitting measures are not performed at the same time. Previous studies [10] on historical energy performance and deep renovation trends in the German's residential building stock proved that in many buildings single renovation measures (only windows replacement, or only roof insulation) have been performed. Beyond that, Steiger [4] affirmed that in real life, most retrofit activities are performed step-by-step sequences, and Menassa [11] presented financial advantages of multi stage retrofitting. Thus, step-by-step renovation modelling deals with following questions: how to define a renovation step? Which retrofitting measures are performed in a step? When are they performed? In which sequence are they performed?

#### Outlining the step-by-step optimisation approach

In the step-by-step concept, a step consists of combination of one or more retrofitting measures. The literature review showed that common retrofitting measures are: insulating building elements external walls, roof (or top floor ceiling) and floor, replacing windows, and active system (heating, cooling, ventilation, lighting and domestic hot water). In real-life, other aspects like construction site preparation and scaffold costs, are also relevant to define, if the measures will be performed together, or not.

During a building's life cycle, maintenance and operation activities constantly happen to avoid first stages of degradation and failure of building elements [12]. At the same time, usual maintenance activities and/or material replacement provide an opportunity for increasing building element's energy efficiency, and consequently improving building's energy performance. Refurbishment activities can be induced by unpredictable damages, as breaks, leakages and cracks, familiar circumstances i.e. children birth and family members move out, etc. Or predictable parameters, as material's durability, which defines the material's lifetime. In a study about factors influencing German house owner's preferences on energy retrofits, the authors [13] concluded that most homeowners have a rational behavior to wait until building components end of their useful life before approaching renovation or replacement. Therefore, predicting the building materials' aging process helps to determine the timing aspect of the step-by-step approach.

Together with technical aspects, in single family houses retrofitting, the homeowners are a key decision maker. On a study about drivers of thermal retrofit decisions, the authors pointed that the upfront costs are a key barrier to the pursuit of building retrofit [14]. Thereupon, the second important parameter refers to economic aspects. Some authors [5] [8] included the budget restriction in their models, however as a fixed value without a method justification. A plausible assumption is to address existing assets for retrofitting (based on family's income and available budget).

#### 3. Method

This chapter outlines a method for step-by-step optimisation modelling from building owners' perspective. The main target is to maximize the net present value of (cumulated) income available for energy related expenditures minus energy related expenditures over a certain optimisation period. It is assumed, that the building owner 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).

## **Objective Function**

The optimisation model should find solutions for maximising the net present value according following objective function:

$$\max NPV = \sum_{t}^{T} \frac{CF_{t}}{(1+r)^{t}} + \frac{L_{T}}{(1+r)^{T}}$$

*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 [%]; t, time [a]; *T*, optimisation period [a].

# 3.1. Cash flow of energy related balance

The energy related economic balance (cash flow CF) of the building owner (assuming an owneroccupied building) in every year t is the shared of household's income (CF) (see also 3.1.1.) minus the energy related expenditures (IC, EC and OMC) (see also 3.1.2. to 3.1.4.):

$$CF_t = INC_t * s - IC_{er,t} - EC_t - OMC_t$$

Equation 1

Equation 2

*CF*, cash flow of energy related balance; *INC*, household income [EUR]; *s*, allocation factor of total annual income on energy related expenses [%]; *IC*<sub>er</sub>, energy related investment cost of retrofitting measures [EUR]; *EC*, annual running energy costs [EUR/a]; *OMC*, annual running operation and maintenance costs [EUR/a].

## 3.1.1. 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) which is allocated for energy related expenses (including running costs and investments) and previous assets  $(A_{t-1})$  and energy related expenses:

$$A_t = (INC_t * s) - IC_{er,t} - EC_t - OMC_t + A_{t-1}$$
 Equation 3

*A*, cumulated allocated energy related asset [EUR]; *INC*, household income [EUR]; *s*, allocation factor of total annual income on energy related expenses [%]; *EC*, annual running energy costs [EUR/a]; *OMC*, annual running operation and maintenance costs [EUR/a].

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

$$B_t \ge IC_{er,t} + EC_t + OMC_t$$
 and  $p_t > 0.05$ 

with

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

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

#### 3.1.2. Investment costs (IC)

The total retrofitting investment costs ( $IC_{tot}$ ) in year (t) are determined by the sum of energy related investment costs ( $IC_{er}$ ) and the maintenance investment cost ( $IC_{man}$ ) for each retrofitting measure, which has to be carried out for reasons of security or aesthetics: building envelope (external wall, window, floor or roof) and active system (heating, cooling, domestic hot water) (i), considering the probability of material's aging process (p) (see 3.2.) and a binary variable ( $x_t$ ), which indicates if the measure is performed or not:

$$IC_{er,i,t} = \sum_{i} [(1 - p_{t,i}) * IC_{man,i} + IC_{er,i}] * x_{t,i}$$
 Equation 4<sup>1</sup>  
where,  $x_{t,i} = 1$  or 0

<sup>&</sup>lt;sup>1</sup> The approach could be extended by distinguishing different efficiency levels of different renovation measures (d.h. insulation thickness) by adding an additional index j for these levels, where the additional restriction has to be fulfilled that the sum over j of  $x_{t,l,j} \le 1$ .

 $IC_{tot}$  total investment costs [EUR];  $IC_{er}$ , energy related investment costs of renovation measures [EUR];  $IC_{man}$ , maintenance investment cost of renovation measures [EUR]; x, binary variable (1 or 0) [-]; p, probability of material's aging process [-]; A, annually allocated energy related asset [EUR].

The assumption behind this equation is, that the investment costs for the maintenance of a renovation measure  $(IC_{man,i})$  only has to be considered as an energy related expenditure, if there is no necessity to renovate a certain building component due to the life time. If the probability that a renovation measure has to be carried out is close to 1, then,  $IC_{man}$  is not relevant for the energy related investment decision, because the measure has to be carried out anyway.

## 3.1.3. Energy costs (EC)

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:

Equation 5

6

Equation 7

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

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,

$$\begin{array}{ll} x_t = 0, & fed_{t+1} = fed_t \\ x_t = 1, & fed_{t+1} = fed_t * f(IC_{er,i}) \end{array} \end{array}$$
 Equation

## 3.1.4. Operation and maintenance costs (OMC)

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 ( $f_{OMC}$ ):

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

*OMC*, operation and maintenance costs [EUR/a];  $IC_{er}$ , energy related investment costs of active system [EUR]; f; operation and maintenance factor [%].

# 3.2. Material's aging process probability (p)

The probability (p) of a retrofitting measures (i) at the time (t) is defined by the Weibull distribution of material's aging process [15]:

$$p_{i,t} = 1 - e^{-\left(\frac{t-t_{i,0}}{t_{i,L}-t_{i,0}}\right)^m}$$
, where t, t<sub>0</sub>, m>0 Equation 8

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

If the material is retrofitted, than the aging process restarts: For:  $(t, t, n)^m$ 

$$x_{i,t} = l, \quad p_{i,t+1} = 1 - e^{-\left(\frac{t-t_{i,0}}{t_{i,L}-t_{i,0}}\right)^m}$$
 Equation 9

3.3. Residual value (L)

The residual value at the time (t) of the retrofitting measures (i) is related to material's technical lifetime  $(t_L)$ , depreciation time  $(t_P)$  and energy related investment cost:

$$t < t_{L,i}$$
:  $L_T = \sum_i \sum_t IC_{er,t,i} * \frac{(T-t)}{t_{L,i}}$ 

 $t \ge t_{L,i}$ : 0 Equation 10

*L*, residual value [EUR]; total investment costs [EUR];  $t_L$ , technical lifetime [a]; *T*, optimisation period time [a]; *t*, retrofitting time [a].

## 4. Conclusions

A literature review showed several approaches for optimisation models of building retrofitting. Despite their particularities in terms of energy performance calculation method and objective function, all methods consider that the retrofitting measures are performed at the same time, so called single stage retrofitting.

In this context, the present study proposes a framework on how to apply retrofitting optimisation models for step-by-step retrofitting approach by formulating a corresponding optimization problem. Our focus are owner occupied single family houses, and therefore, the optimisation framework considers the building owner's perspective. The proposed method aims at maximizing the net present value, which represents the balance between energy related expenditures, and existing assets for retrofitting (based on family's income and available budget).

In the step-by-step concept, a step consists of combination of one or more retrofitting measures at a point of time. A single stage approach can be broken down in numerous renovation steps: building envelope measures – roof, external wall, floor insulation and windows replacement- and active system measures for heating, cooling, ventilation, heat distribution, lighting and domestic hot water. In real-life, lock in effects and thermal bridges have to be take into account. Also, construction site preparation and scaffold costs also affect the aggregation of one- or two measures. Nevertheless, future studies should try to further identify retrofitting measures aggregation boundaries.

To define the timing of the each retrofitting step, the probability of material's aging process distribution [15] in combination with available asset was proposed. We assume that the budget restriction of the investments in maintenance renovation works is not correlated to the budget restriction of the energy related expenses. This might be a simplification, which will be revised in a later stage.

# 5. Discussion and future outlook

Future planned activities of this study will include testing and extending the optimisation model, as well as, applying its results to a building stock scale and analysing possible impacts of step-by-step renovation measures on the achievement of building stock's decarbonisation targets.

To guarantee accuracy, sensitivity analyses will need to include important parameters as income projection, energy price scenarios and policies.

Further plausibility analyses should include human behaviour aspects (i.e. rebound effect), market value of the building after retrofitting, ambitious of building energy codes in terms of energy efficiency, as unpredicted incomes and assets (e.g. bonus or inheritance).

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