Dissertation

The role of staged retrofits in the space heating decarbonisation of residential buildings

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Abstract

Studies that have attempted to investigate why the insufficient decrease in buildings' energy demand identify economic barriers (e.g. budget restrictions) as prime hindrances. These barriers lead in real life to the gradual performance of renovation activities, called "staged renovation" by the Energy Performance of Buildings Directive. The present thesis aims to bridge the gap between building renovation modelling and real-life practices and contributes to the current literature by deeper investigating households' budget restrictions to renovate, calculating the time perspective of staged renovation and assessing their effects on achieving the climate targets. The following research questions are answered: 1) How can existing datasets (HBS, EU-SILC) be merged to generate techno-socioeconomic datasets and provide household-specific insights about building retrofitting triggers? 2a) For delivering the optimum timing of staged renovation, which techno-economic parameters should be considered in an optimisation model? 2b) To which parameters and variables is the model sensitive? 3) Which insights about staged renovations and their impacts on CO_2 emissions can be observed when assessing different buildings? Two developed, tested and demonstrated methods answer these questions and represent the novelties of this work. The first method allows for statistically matching the data sources HBS and EU-SILC via logistic regression. The second method is a mixed-integer optimisation model that calculates the optimum timing when each renovation stage should be performed. The first case study compares cost- and climate-optimal variants of different energy efficiency measures for reference buildings in Spain, Germany and Sweden. The second case study focuses on the country of Spain, building on results obtained throughout the work. This case study assesses the staged renovations time perspective of the cost-optimal variant applied for Spanish reference buildings under a data-driven available budget. The first results showed that building renovation models should consider techno and socio-economic heterogeneities. Because of that, the developed mixed-integer optimisation model builds on techno-economic parameters, such as homeowners' available budget and the building material ageing process. By analysing data from Spain, rented single-family houses were identified as the most vulnerable household type due to their low average income. Owner-occupied single-family houses have the highest natural gas expenditure, however, the results indicate that high natural gas expenditures alone are not a trigger to renovate. The optimised roadmaps had a total time between 5 and 12 years, depending on the building characteristics and the budget available. Sensitivity analyses were performed for energy prices, initial investments, interest rates, different combinations of measures per stage and interrupted roadmaps. The present thesis concludes that to decarbonise the building stock well-coordinated mix of single-stage and staged renovation activities is needed. As policy recommendations, the present thesis suggests a clear definition of a maximum of stages and the minimum energy performance per stage by designing building renovation passports to avoid lock-in effects. Furthermore, this thesis advises using metrics that represent the time perspective of building renovations (for example, cumulative CO_2 emissions) to monitor the building stock decarbonisation as foreseen by the national long-term renovation strategies.

Abbreviation

AT	Austria
BG	Bulgaria
BRP	Building renovation passport
BSO	Building Stock Observatory
CO_2	Carbon-dioxide
DE	Germany
DHW	Domestic hot water
EED	Energy Efficiency Directive
EPB	Energy Performance of Buildings
EPBD	Energy Performance of Buildings Directive
EPC	Energy performance certificates
EU	European Union
EU-SILC	European Union Statistics on Income and Living Conditions
ES	Spain
FR	France
HBS	Household Budget Survey
iBRoad	Individual building renovation roadmap
ID	Identification code
IT	Italy
IPCC	Intergovernmental Panel on Climate change
LCA	Life Cycle Assessment
LCC	Life Cycle Cost
LAU	Local administrative unit
LTRSs	Long-term renovation strategies
MEPs	Minimum energy performance standards
MILP	Mixed-integer linear programming
MFH	Multi-family houses
MSs	Member States
NL	The Netherlands
NPV	Net present value
NUT3	Nomenclature of territorial units for statistics
nZEB	Nearly zero emission building
PL	Poland
PT	Portugal
ROC	Receiver operating characteristic
RO	Romania
RQ	Research question
SE	Sweden
SFH	Single-family houses

Units

Abbreviation	Variable	Unit
CF	Cash flow	euro
ASS	Asset	euro
A	Area	m^2
B	Available budget	euro
Ca	Operational costs during the year	euro/year
Cg	Global costs	euro
CES	cumulated energy savings	%year
CO2	Carbon emission	$kgCO_2$
CO2sav	Carbon emission savings	%
EC	Annual running energy costs	euro
ES	Energy savings per stage	%
f	Operation and maintenance factor	%
fed	Final energy demand	kWh
IC (or C_I)	Initial investment	euro
INC	Annual income	euro/year
L (or $V_{f,\tau}$)	Residual value	euro
fl	Loan or available incentive factor	%
NPV	Net present value	euro
OMC	Annual operation and maintenance costs	euro
p	probability of materials' ageing process	[-]
pr	energy price	euro/kWh
r	Interest rate	%
Rd	discount factor	%
s	Income share factor	%
T	Optimisation period	year
t	time	year
t0	period without failure	year
tL	technical lifetime	year
tp	Depreciation time	year
τ	calculation period	year

Content

1 Introduction

1.1 Motivation

Since the Industrial Revolution in 1750, human activities have increasingly emitted carbon dioxide (CO_2) into the atmosphere faster than natural processes can remove it (Lüthi et al. 2008). Consequently, global warming caused by increased CO_2 concentration in the atmosphere has threatened human existence on Earth. Therefore, there is an urgent need for global efforts to reduce CO_2 emissions. According to World Data (Oxford 2022), the European Union (27) presents the second-highest cumulative CO_2 emissions worldwide, only being surpassed by the United States.

In recent years, the European Union has set more stringent strategies and targets to reduce CO_2 emissions. However, in the building sector, there have been few successes. Regarding CO_2 emissions, the building sector is critical, as buildings are responsible for about 40% of energy consumption and 36% of CO_2 emissions (European Commission 2018). Despite the political effort, statistics about final energy consumption in households (Eurostat 2018a) and the share of final energy consumption per fuel (Eurostat 2018b) have shown that there is still a long pathway to achieve the EU targets. In 2020, 32.1% of households' final energy consumption was covered by natural gas data (Eurostat 2020a) in the EU-Member States. The same source presents that 85% of household energy consumption is for space and hot water heating and cooking, respectively 64%, 15% and 6%. The remaining 15% of household energy consumption is for electricity (lighting: 14%; space cooling: 0.4%; and 1% for other end-uses, e.g. household devices).

Furthermore, the COVID-19 pandemic and the Russian-Ukrainian war have affected energy consumption patterns, and the EU's heating system decarbonisation has become even more urgent to assure fuel energy supply security. In this context, renovating Member States' buildings is discussed as one of the strategies to decrease fuel dependence. However, only 11% of the building stock currently undergoes any yearly renovation activity. Whereas the weighted annual renovation rates are 1% per year, only 0.2% per year for deep renovations (that reduce energy consumption by at least 60%)(European Commission 2022).

Two crucial legislative instruments aim to promote the increase of buildings' renovation rate and achieve a high energy efficient and decarbonised building stock: the Energy Performance of Buildings Directive (EPBD) and the Energy Efficiency Directive (EED). The present thesis relies strongly on the EPBD, providing scientific contributions to different aspects of this directive (as explained below).

Since 2017 (when the work on the present thesis started), the policy context of building stock decarbonisation has passed through many significant changes, starting in 2018 with an EPBD recast. Furthermore, in 2021, the European Union launched the European Green Deal strategy, showing the strong commitment to acting against climate change and the high ambition to become a climate-neutral continent by 2050. The "Renovation Wave" is part of the European Green Deal strategy that exclusively addresses the building sector and formulates the goal of at least doubling the annual buildings' renovation rate by 2030. Regarding buildings' energy consumption, the Renovation Wave sets the following targets: reducing by 60% CO_2 emissions, by 14% final energy consumption and by 18% buildings' energy consumption for heating and cooling until 2030 compared to 1990 (European Commission 2020).

Since 2021, there has been a new proposal for an EPBD recast (European Commission 2021) that the directive is also in line with the Renovation Wave as summarised by Wilson (Wilson 2022). The document proposes the following measures (European Parliament 2022):

"

1. *a definition of deep renovation and the introduction of building renovation passports;*
2. *the gradual introduction of minimum energy performance standards (MEPs) to trigger renovation of the worst-performing buildings;*
3. *modernisation of buildings and their systems, and better energy system integration (for heating, cooling, ventilation, charging of electric vehicles, renewable energy);*
4. *increased reliability, quality and digitalisation of Energy Performance Certificates; with energy performance classes to be based on common criteria;*
5. *enhanced long-term renovation strategies, to be renamed national Building Renovation Plans;*
6. *a new standard for new buildings and a more ambitious vision for buildings to be zero-emission.*

"

This thesis is directly embedded into the first bullet point above. The EPBD 2018/844/EU recast introduced the building renovation passport (BRP) that provides tailored advice on improving the building's energy efficiency. The BRP entails a "step-by-step" and "long-term" renovation roadmap, which is this thesis's central topic. The present work focuses on the residential building stock, specifically the owner-occupied single-family houses. The main contribution refers to the assessment and better understanding of the stage retrofitting aspects that influence the time perspective of how fast the achievement of the decarbonisation targets for the residential buildings happens.

Nevertheless, the staged retrofits consider envelope and heating supply measures necessary to significantly reduce buildings' CO_2 emissions and space heating energy demand. In this context, a more in-depth discussion about the terminology related to "stage" and "renovation" is presented in Chapter 3.1. Chapter 3.5 presents more details about the BRP and other policy-related elements existing in the EPBD. Chapter 1.2 presents the objective and the research questions of the present thesis. Finally, chapter 1.3 presents the structure of the thesis, and a chapter overview, including all chapters.

1.2 Objective and research questions

The present thesis has as its core objective to forge a better understanding of the role of staged retrofits in the decarbonisation of the residential building stock. The current thesis aims to bridge the gap between renovation modelling and real life building renovation practices by taking a closer look at staged renovation's role in decarbonisation and investigating economic barriers to renovation. The present work indirectly contributes to accelerating the building stock renovation activities and consequent decarbonisation of the buildings. For that, in-depth techno-economic analyses were performed, to answer three research questions related to the following topic areas:

- the **technological and energy-economic aspects** of a retrofitting project, including differences between single-stage and staged retrofitting, building-specific characteristics, and space heating supply;
- the **energy and socio-economic aspects** of a retrofitting project, including energy carrier prices, initial investments, budget restrictions, and interest rates;
- the **current policy framework** and possible policy recommendations to accelerate buildings' retrofitting rates.

The next paragraphs briefly explain the topic areas mentioned above and present the research questions that address each of these areas.

A building retrofit has the prime driver to increase energy performance by generating energy savings. The measures implemented in a retrofit project typically remain for many years (according to the lifetime of the materials), which means that ideally, the project should exhaust and fully exploit the energy savings potentials. With that achieved, long-term energy saving can be guaranteed. Otherwise, lock-in effects occur, and the building stays for a long time with lower energy performance than it could (or should) have. Therefore, on the one hand, technical aspects should be taken into consideration when planning a building retrofit: the time when the measures are performed; the combination of measures or package of measures; the sequence of implementing the measures; the technologies and materials to be installed; and the technical implementation through skilled craftsmen.

On the other hand, the building owner's economic aspects and socio-economic characteristics play a relevant role. The economic factors are the potential energy cost savings affected by the energy prices, the initial investments, the building owner budget restrictions, and available incentives and financial conditions for granting debits by the banks. Finally, socioeconomic aspects of building owners such as marital status, age, family composition, education, and the degree of urbanization of the area are also determinants for the choice of undertaking a retrofit project.

The present thesis covers, to some extent, the areas mentioned above by providing a techno-socio-economic analysis of staged retrofits and answering the following research questions:

Research question 1: *How can existing datasets (HBS, SILC) be merged to generate techno-socio-economic datasets and provide household-specific insights about building retrofitting* *triggers?* Research question 1 addresses different aspects. First, it provides a classification of households according to dwelling type and ownership status, expanding the currently used building typology based on the technical and geometric characteristics of the building. Second, it addresses the issue of household budget restrictions to afford retrofitting projects. Finally, a developed workflow demonstrated and tested how two different datasets can be merged using statistical matching via logistic regression. The EU datasets are the Household Budget Survey (HBS) and EU Statistics on Income and Living Conditions (SILC). The contribution to this question also discusses natural gas expenditures and under which circumstances it is a trigger to perform retrofitting. Beyond that, the role of incentives and financing schemes to increase retrofitting rates is discussed. Summarised, the following points below are linked to this research question:

- Classify household types according to the characteristics: dwelling type and ownership status.
- Use existing EU datasets to provide data-driven insights specifically about income, budget restrictions, natural gas expenditure, and possible triggers to retrofit.
- Develop a robust method to match both datasets, EU-SILC and HBS.
- Identify and differentiate vulnerable, "able to pay" households and "able to pay" supported by incentives (or financing schemes) households.
- Provide data-driven input assumptions for the optimisation model.

Research question 2: *For delivering the optimum timing of a staged retrofit, which techno-economic parameters should be taken into account in an optimisation model? To which parameters and variables is the model sensitive?* Research question 2 addresses an optimisation modelling concept based on techno-economic pillars. To address this question, the model developed calculates the optimum timing when each stage should be performed and, consequently, calculates the total time needed to complete all stages of a building roadmap. The contribution to this question also discusses the specific technical aspects that should be considered when defining an individual building roadmap, the differences between single-stage and staged retrofit approaches and the model's sensitivity to parameters such as energy prices and initial investments.

- Develop an optimisation model to calculate the optimum timing in each stage.
- The model outlined is based on techno-economic parameters.
- Verify parameters that have a stronger influence on the total roadmap time.
- Prepare the model to be used in further analysis.
- Provide insights about differences between single-stage and staged-retrofit in terms of timing.

Research question 3: *Which insights about staged renovations and their impacts on CO_2 emissions can be observed when assessing different buildings?* Research question 3 investigates the effects of staged retrofits on a building stock. The results from research questions 1 and 2 are combined. The data-driven budget restrictions addressed by the first research question are used as input data in the staged retrofit optimisation model developed to address the second research question. In this study, not only data-driven budget restrictions but also different building typologies are considered. Finally, this research question improves the current policy framework regarding staged retrofits by assessing possible impacts on building stock decarbonisation and providing policy recommendations.

- Apply data-driven assumptions to the optimisation model.
- Use established metrics for economic assessment, such as global costs and net present value, and climate-targeted metrics as cumulative CO_2 emissions.
- Analyse the effects of the data-driven budget restrictions on the roadmap time for different reference buildings (especially for the case study of Spain).
- Analyse the effects on the optimised roadmap time of different energy efficiency standards and countries for reference buildings in Spain, Germany and Sweden.
- Analyse the effects of a material lifetime on possible renovation cycles (case study for Germany).
- Address policy recommendations on concretely improving the existing policy elements related to staged retrofit and renovation activities.

1.3 Structure of the thesis

Figure 1 presents an overview of the present thesis' structure. The present thesis is divided into eight chapters, including the content of different scientific contributions, such as journal publications, peer-reviewed conference papers and conference presentations - Appendix I: Overview publications and scientific contributions.

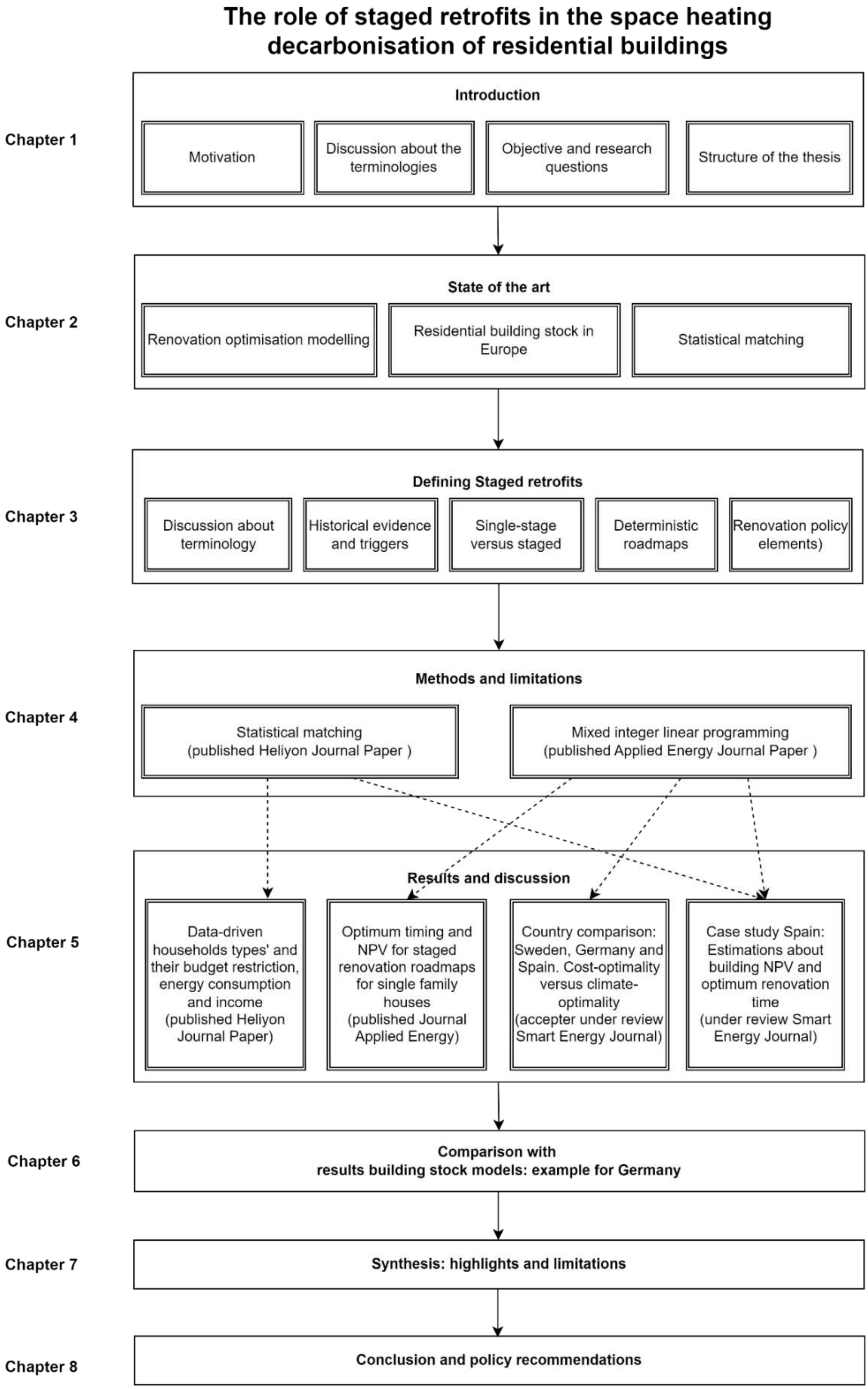


Figure 1: Thesis structure overview

2 State of the art

This chapter describes the current state of the art of the EU residential building stock, including existing semantics for building typologies and the main socio-economic barriers for renovation activities (Chapter 2.1). With that, this chapter explains the main problem addressed by the thesis. Furthermore, chapters 2.2 and 2.3 present, respectively, the retrofit optimisation models and the statistical matching using EU-SILC and HBS data sources. With that, the literature review of the methods developed and demonstrated is presented.

2.1 EU residential building stock: building typologies and socioeconomic barriers for renovation activities

The building stock is divided into residential and non-residential buildings. Residential buildings are those mainly designed for the purpose of living. Non-residential buildings comprise all others buildings types, i.e., offices, educational, hospitals, wholesale, retail, hotels, restaurants etc. The authors estimated 25 billion m² floor space, with 75% being residential and 25% non-residential buildings in the EU-27, Switzerland and Norway (Economidou et al. 2011).

The EU-H2020 Project Hotmaps also studied the building stock. The project calculated the shares for both residential and non-residential buildings divided into different construction periods (before 1945 until after 2010) (Pezzutto et al. 2019). Figure 2 shows that more than 50% of the buildings were constructed before 1979, 54% (residential) and 53% (non-residential). However, this is a period when building construction practices did not incorporate energy efficiency standards, indicating low energy performance of the buildings (especially if no retrofit activity was performed in the period). Furthermore, the buildings constructed before 1945 have the highest shares, 20% (residential) and 24% (non-residential), emphasizing the old character of European's building stock.

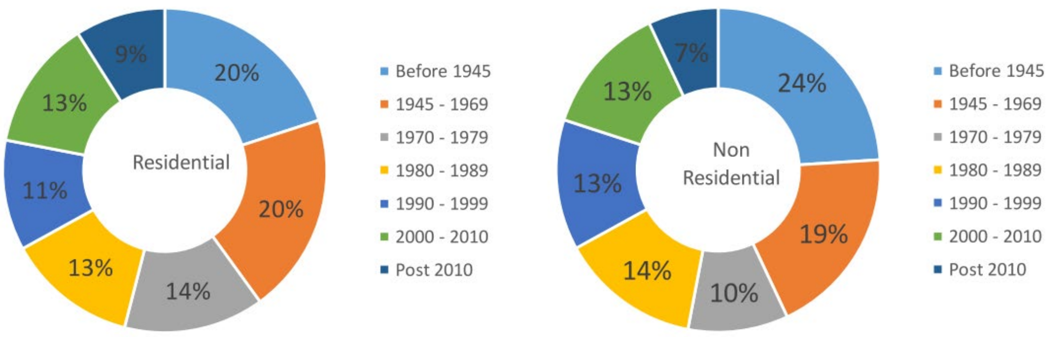


Figure 2: Building stock share per building type (residential and non-residential) and per construction period (before 1945 until after 2010). Source: (Pezzutto et al. 2019)

Figure 3 shows the shares per building type sub-category. Between the residential buildings, single-family houses have the highest share (68%), followed by multi-family houses (24%) and apartments (8%). The non-residential buildings are more diversified, having trade buildings with the highest shares (45%), followed by offices (21%), hotels and restaurants (12%), others (11%), education (6%) and health (5%).

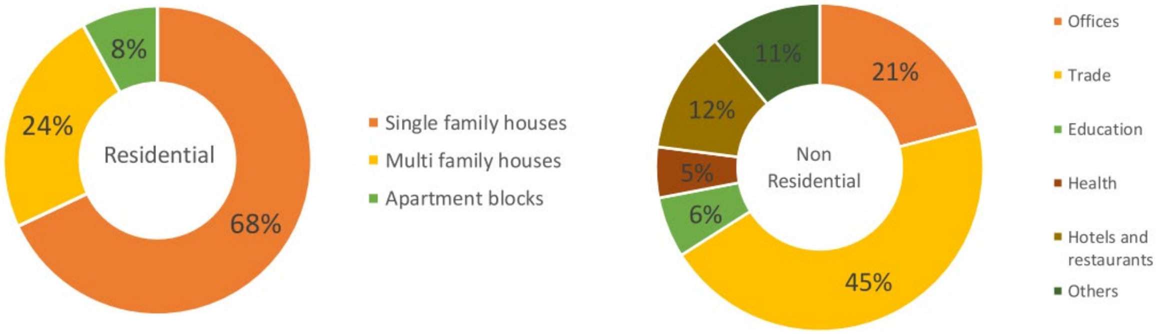


Figure 3: Building type sub-categories share. Source: (Pezzutto et al. 2019)

Naturally, the national shares and specific building characteristics differ in each EU-countries. Then, the EU-funded project TABULA web tool described national building typologies for the residential building stock, making evident the individual character of each country (EPISCOPE project 2016). The typology systematic consists of identifying similar buildings and describing the building characteristics by dividing the buildings per size and construction age classes. For each typology, for example, the project described the size, geometry, energy efficiency (U-values per building element), heat supply system and energy-saving measures (two quality levels). The information provided by the TABULA web tool was used in different stages of the present thesis, especially by performing the case studies for Germany and Spain. Figure 4 shows a screenshot of the web tool for Germans residential buildings. Per construction period (construction year class), the typologies SFH (single-family house), TH (terraced house), MFH (multi-family house) and AB (apartment block) are specified. On the right-side overall information about the typology is provided, as reference floor area, climate region and energy performance indicators (energy need for heating, energy carriers, primary energy non-ren. etc.). By clicking on the left side on building data and system data, the user sees more information as U-value per building element, area per building element etc.)

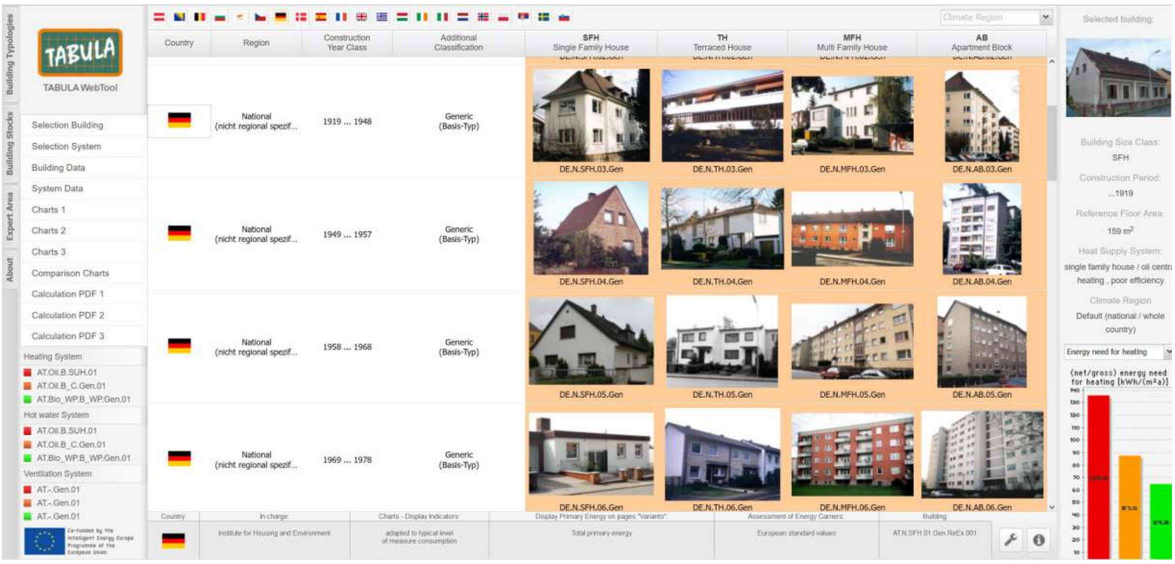


Figure 4: Screen-shot of the TABULA web tool, an example of German typologies. Source: (EPISCOPE project 2016)

Another relevant web tool that contains building stock relevant information is the Building Stock Observatory (BSO) (European Commission 2016). This is a European Union tool to monitor the energy performance of buildings; therefore, it collects and centralises information and provides data mappers and factsheets about the Building Stock information, covering the following topic areas: building characteristics, energy consumption, energy mix, energy performance and technical building systems, building certificates, financing and energy poverty and social aspects. Currently, the EU-funded project BuiltHub demonstrates how the BSO can be improved in terms of stakeholder engagement as a data provider, database structure, data analysis and data visualisation (BuiltHub 2021).

EPC databases store EPCs and underlying data making them a relevant building stock information source that simultaneously contains disaggregated building information. EU-wide, there are well-established and reliable EPC databases used by national public authorities that also interoperate with other databases such as registry and incentives databases. The EU-funded X-tendo project identified the best-practices examples as the Danish database operated by Danish Energy Agency (DEA 2020) and in Scottish database (EST 2020) operated by Energy Saving Trust (EST). The project developed an automatised and risk-based EPC quality control routine methodology to increase the reliability of EPC databases (X-tendo 2021). With that, the project also demonstrated activities to explore the potential of EPC databases that have a huge potential to support the improvement of the existing building typologies. Besides that, the EPC databases can interoperate with other registries strengthening even more, their potential has building and building user-related information sources. Socio-economic barriers to renovation activities

Previous studies have identified different barriers to low building renovation activities: **technical** (lack of expert craft men or knowledge to perform the renovation (Fabbri, Volt, and de Groote 2018b)), **acceptance** (mistrust or scepticism of new technologies or improvement measures (Filippidou, Nieboer, and Visscher 2017)), **legal** (different interest of parties involved, for example, the landlord-tenant dilemma(März, Stelk, and Stelzer 2022)), **economic** (building owner savings or affordability to invest in a retrofit (Fabbri, de Groote, and Oliver 2016)) and **financial** (lack of attractive financing and incentive schemes(Bertoldi et al. 2021)). In fact, the mentioned barriers are not necessarily independent or isolated from each other, which makes the reasons even more complex for building owners not to undertake a retrofit(Tugran et al. 2021). Beyond that, renovating a building element or replacing a component does not necessarily mean that high energy efficiency standards are achieved (Friege and Chappin 2014). Consequently, it calls for new approaches and innovative solutions to solve this problem and to turn building renovation into activities that generate increased energy efficiency while reducing CO_2 emissions.

Retrofitting can be treated as a single topic area related to buildings and their technical aspects. However, it may not be sufficient to considerably upscale the activities to achieve the targets. The present thesis contributes to the current literature by also researching economic aspects of retrofitting activities, which includes a holistic view of the households' available budget (considered a relation between the incomes and the expenditures). This means, beyond only energy-related expenditures, considering all expenditure categories included in the HBS data. Figure 5 shows the share of households' final consumption expenditure per category in the EU based on HBS data from 2015. The highest expenditure share is 24.4 % for housing, water, electricity, gas and other fuels. Additionally, 5.4% is for furnishing, household equipment, routine household and maintenance. Together, both categories account for almost 30% of the expenditures, which is a significant burden and relatively higher than any other category. The second category is "Transport" with 13%. Beyond that, the present thesis analyses specifically and separately the energy expenditures (in the session results 4.1), which are indirectly represented by the category "housing, water and energy expenditure". The main goal was to better quantify that even high energy expenditure can be a trigger for retrofitting.

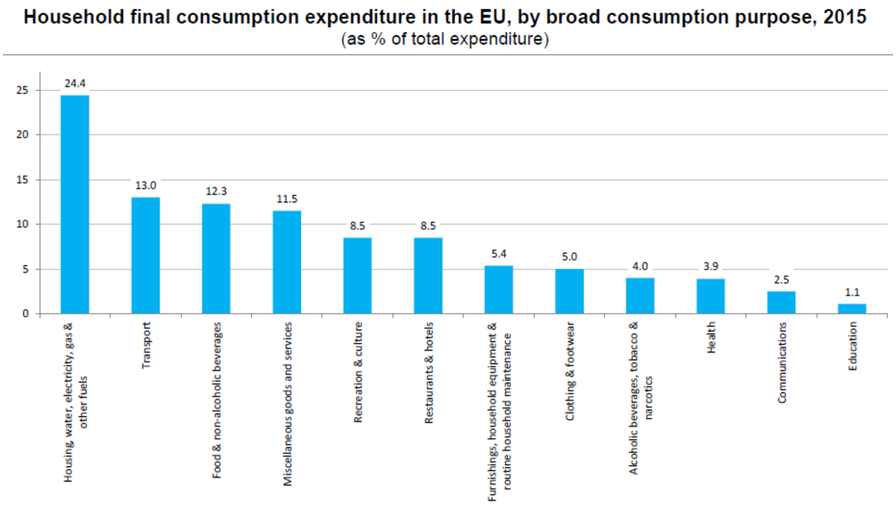


Figure 5: Household final consumption expenditure in the EU per expenditure category (%),2015. Source: [26]

In fact, in real life, the decision to undertake retrofitting measures is a very individual and subjective one. A study about citizens' motivations and barriers to engaging in energy efficiency renovation showed that the decision to carry out renovation also depends on diverse personal socio-economic, geographical and cultural characteristics(Ipsos 2018). Then, the housing ownership status is a socioeconomic characteristic relevant to retrofitting projects. This characteristic indicates who will be involved in the decision-making process, who will invest and under which budget constraints and which are the main interests. Therefore, it is important to distinguish between decision maker, investor and beneficiary (I. Maia, Mellwig, et al. 2020). The decision maker is normally the building owner or manager on behalf of the owner and responsible for fulfilling specific regulations, expectations or requirements. The investor is financially responsible for the building retrofit. The beneficiary derives the direct benefits of using the building and is normally the owner or the tenant. In certain cases, the decision maker may also be the investor and/or the beneficiary. For example, in an owner-occupied single-family house, the decision maker, the investor and the beneficiary are the same person. In this case, the owner invests in the retrofit and also directly benefits from its multiple benefits (e.g. energy cost savings and better comfort etc.). In a rented apartment, the decision maker and beneficiary are not the same people - the building owner might be a private person, private company or public authority, whereas the beneficiary is the building user and renter. In rented offices, the direct beneficiary is the workers, the decision maker, the company that rents the building, and the investor, the owner of the building (for example, a real estate company).

Then, the existing ownership status is (I. Maia, Mellwig, et al. 2020):

- **Owner-occupied**: that is the only category where the building user and the building owner are the same party. It might also be a public authority in the case of non-residential buildings. The private owner-occupied can be the outright owner (no outstanding loan or mortgage for his main residence) or the paying mortgage owner.
- **Privately rented**: tenants pay rent to landlords at a market price. Landlords (private persons or companies) pursue commercial purposes.
- **Socially rented**: tenants pay a subsidised rent (reduced rent or for free) to landlords, usually public entities or housing associations.

Also, the different building owner types are:

- **Private**: private persons or companies, for example, real estate companies;
- **Public**: public entities or housing associations

Using only EU-SILC data, Figure 6 shows the share of households characterised by the dwelling type (SFH and MFH) and the housing ownership status (outright owner, tenant, for free, owner paying a mortgage and reduced rented) in ten European countries: Austria (AT), Italy (IT), Spain (ES), Romania (RO), Sweden (SE), Poland (PL), Bulgaria (BG), Portugal (PT), France (FR) and Netherlands (NL). While single-family houses can be detached or semi-detached, multi-family houses can be small or big apartments.

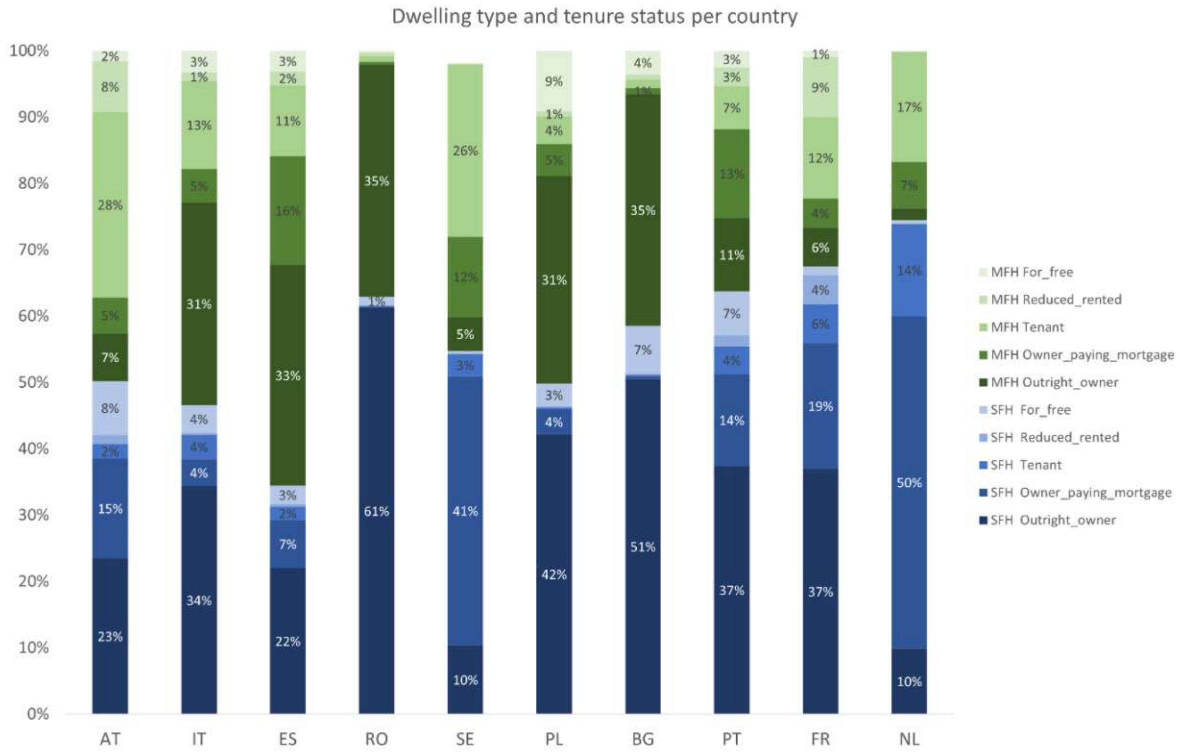


Figure 6: Dwelling type and ownership status per country. Source: Own graph based on EU-SILC 2020

Figure 6 reveals the share of SFH (in blue) and MFH (in green). When the ownership status is also considered, the heterogeneity and the country-specific singularities of the housing market become more evident. Four clusters of countries are identified: very diversified, diversified (with a high share of outright owners), high share of outright owners and a high share of single-family houses paying a mortgage.

In general, the share of SFH varies between 34% in Spain and 74% in the Netherlands. Austria is the country with the most diverse share of the various types, whereas no type exceeds more than 30%. Spain, Portugal, Italy and France are diverse, with no type exceedingly more than 40% share. In Romania (61%), Bulgaria (51%), and Poland (42%), the outright owner of single-family houses is the dominant type. Then, Sweden (41%) and the Netherlands (50%) are the countries with a high share of owner-paying mortgage single-family houses.

Then, the present thesis contributes to the present literature by considering building typologies defined by the dwelling type and the ownership status. For these groups, also the budget restrictions are more precisely quantified based on data-driven analysis. In general, a better understanding of how the combination of these factors facts the chosen retrofitting approach and consequently time perspective.

In sum, in real life retrofit projects that are not single-stage, there is still a dilemma between performing “short-term” and “long-term” measures. In the first, a holistic plan is not considered, and measures are performed according to the demand – which is randomly defined. While in the second, long-term planned measures consider individual priorities and possibilities (e.g. household’s available budgets) in a building renovation roadmap (IBRRs).

Technically speaking, the “short-term” solution is often not the ideal one if a lock-in effect is generated by not exploring the highest energy-saving potential or an inefficient operation of the technical system. For example, the heating system is replaced before improving the building envelope. The technical aspects of staged retrofitting, including the differences from the single-stage approach, are presented in the next chapter.

2.2 Retrofit optimisation modelling

Retrofitting optimisation models aim 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. A number of studies and retrofitting models were reviewed before outlining, developing and testing the staged retrofit optimisation model (see more details in Chapter). Pombo, Rivela and Neila studied the challenges related to building retrofitting (Pombo, Rivela, and Neila 2016) and presented essential insights to be taken into account by retrofitting models. Another study (Ferreira, Pinheiro, and Brito 2013) presented a review of tools and models to support refurbishment decisions. Emmerich and Deutz developed a tutorial for multi-objective optimisation (Emmerich and Deutz 2018) that is a method used by other authors to assess building retrofitting (Antipova et al. 2014)(Fan and Xia 2017). Other methods used were Monte Carlo Simulation (N. Wang, Chang, and El-Sheikh 2012) and cost-effective calculation based on operational costs (Almeida and Ferreira 2017). 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. Jafari et al. reviewed at least sixteen studies about energy efficiency decision-making, including multi-objective optimisation and other methods such as multi-criteria and a techno-economic evaluation method (Jafari and Valentin 2017). 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 the 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). Some authors compared different retrofitting solutions using a multi-criteria methodology (Pombo et al. 2016). This study combines LCA and 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. developed a model to assist stakeholders in defining measures aiming at minimising the energy needs for heating, cooling and domestic hot water and maximising the investment costs (Asadi et al. 2012). 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. proposed a life cycle cost approach that maximises energy savings and net present value (NPV) while minimising the initial costs (B. Wang, Xia, and Zhang 2014). 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. coupled a degree-days simulation with a generic optimisation procedure algorithm and compared both implemented and calculated retrofit solutions (Murray et al. 2014). This 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 the attic, external walls and windows, boiler type, and infiltration rate. Table 1 presents a summary of the mentioned models in terms of their objective functions, retrofitting approach, consideration of budget restrictions, and type of model

Table 1: Summary of analysed literature review on retrofitting modelling.

Source	Title	Objective Function	Retrofitting approach	Budget restriction	Model
Wu et al.,2017	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	An optimisation framework for building energy retrofits decision making	Minimise life cycle investment	Single-step	Yes	Nonlinear single objective optimisation
Pombo et al., 2016	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	Multi-objective optimization for building retrofit	Minimise retrofit costs Maximise energy savings	Single-step	No	Multi-objective optimisation
Wang et al. 2012	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	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	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	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

The models above differ from each mainly in several aspects: the integration and interface between tools and databases; the renovation measures assumed and the depth of the measures; the energy demand calculation procedures (static or dynamic) and applied modelling method or objective function of the optimisation. However, in terms of the time perspective, any paper explicitly mentions this aspect. This leads to the conclusion that they consider that the retrofitting measures are carried out with the single-stage approach. Seeing that there is a lack of optimisation models for staged retrofit, the developed model specifically treats timing as a vital factor. Also, creating more comprehensive modelling for this alternative retrofitting concept would support the decarbonisation of the building stock due to suitable and right timing measures.

In addition to timing considerations, the staged retrofit model developed also focuses on budget restrictions as a relevant factor. Some authors included the budget restriction in their models, but only as a fixed value without a method justification (Jafari and Valentin 2017) (B. Wang, Xia, and Zhang 2014). The budget restriction is addressed in the developed optimisation model as a share of the household's income and destinated for energy-related expenditures. Moreover, for data-driven assumptions, a method was developed to merge HBS and EU-SILC data sources (see more details in Chapter 5.1, as well as the results in Chapter 5.3.5). Moreover, the effect of different budget restrictions on the optimum timing is presented in the sensitivity analysis (more detail in Chapter 4).

2.3 Statistical matching with EU-SILC and HBS datasets

To assess the current state of the art of EU-SILC and HBS statistical matching, first, the theoretical background of statistical matching is reviewed (chapter 3.3.1). Second, both datasets are described (chapter 3.3.2). Then, the following types of studies were reviewed: studies that use only EU-SILC (chapter 3.3.3), studies that use only HBS Chapter 3.3.4), and studies that carry out EU-SILC and HBS statistical matching (chapter 3.3.5).

2.3.1 Theoretical background of statistical matching

Statistical matching is a mature and broadly used technique to integrate information available in different data sources that cannot be easily integrated, for example, through a common household identification number or another variable. It is often less costly to match datasets than to spend time and money to plan and execute new surveys. Furthermore, due to data protection reasons, it is becoming more difficult to identify households, and statistical matching is a method that helps overcome this type of barrier. This method can be applied in different areas. For example, Macoun et al. applied the method to perform an analysis of the Austrian transport sector receipt dataset based on data from the donor dataset through common variables (Macoun et al. 2018). Figure 7 shows the general concept of statistical matching: the datasets A and B have the common variables (X) and the exclusive variables Y (only available in dataset A) and Z (only available in dataset B). When dataset A is the donor, it means that variable Y will be imputed (or estimated) in dataset B (the receipt).

	Y	X			Z
Base A	y_1	X_i_1	X_j_1	X_k_1	
	⋮	⋮	⋮	⋮	
	y_{nA}	X_i_{nA}	X_j_{nA}	X_k_{nA}	
Base B		X_i_1	X_j_1	X_k_1	z_1
		⋮	⋮	⋮	⋮
		X_i_{nB}	X_j_{nB}	X_k_{nB}	z_{nB}

Figure 7: Matching structure: data from the donor dataset with a recipient dataset based on the common variables X. Source: own illustration

D'Orazio et al.(D'Orazio, Di Zio, and Scanu 2006) describe two approaches to performing statistical matching: macro and micro approaches. In the former, the datasets are used to directly estimate the relation between the variables of interest: it does not lead to the production of a matched dataset. In the latter, the main objective is to construct a synthetic data set. Synthetic, in this case, means that in the recipient dataset, not all variables are directly surveyed information; the variable of interest is imputed or estimated.

In the present paper, the objective is to construct a synthetic dataset; therefore, the micro approach is used. This approach can be non-parametric, parametric or mixed. The non-parametric version imputes live values from one dataset to the other based on predefined criteria (distance, rank, or random in subsets of the data). The parametric method uses a regression model to estimate coefficients with the donor dataset. In the regression, the interest variable (Z) is the dependent one, and the matching variables (X) are the explanatory ones. By using the variable X in the regression equation, the imputed value can be estimated (also explained in Chapter 4.1.2). The mixed method is a combination of these two processes, meaning that both parametric and non-parametric methods are applied.

In the parametric method, a regression model quantifies the correlation between the variables(Harrell, 2015a). The broadly used one is linear regression, where a linear relation between the variables is assumed.

2.3.2 Existing EU datasets for socioeconomic information

The EU-SILC and HBS datasets are important data sources used in various areas of study. The EU-SILC is a survey that collects timely and comparable cross-section and longitudinal multidimensional microdata on income, poverty, social exclusion and living conditions. It is a well-established survey that has been performed annually in EU countries since 2004 ("Interaction of Household Income, Consumption and Wealth - Methodological Issues - Statistics Explained," 2020). The datasets are structured in different files, at an individual and at a household level, which together provides information for more than 100 variables grouped in the following categories: household register, personal register, household data and personal data. The micro-data is anonymised, and the number of observations depends on the country and year.

Examples of information about household conditions provided by the EU-SILC are “ability to keep home adequately warm” or “leaking roof and damp elements”. Although there is also financial information (represented, for example, by the variable “financial burden of the total housing cost”), these are not numerical variables, but rather categorical ones, presented, for example, by the categories heavy, slight or not a burden.

Then, for numerical description and characterisation of household savings and energy expenditures, the information in the EU-SILC alone is not sufficient, for which HBS is the most appropriate data source. The HBS is carried out by each country’s National Statistical Office. Normally, this information is used to update Consumer Price Indices (CPI) and to harmonise the index of consumer prices (HICP) weight structures. Different from EU-SILC, HBS surveys are performed every five years. In the present thesis, 2015 data was used, for which a quality report was published by Eurostat (Eurostat 2020b), as the 2020 data has not been published yet.

2.3.3 Literature using EU-SILC

The literature review identified the use of EU-SILC data in socioeconomic studies that focus on subjective economic well-being (Cracolici, Giambona, and Cuffaro 2012), income and inequality (Hlasny and Verme 2018), and deprivation and social exclusion (Pisati et al. 2010). In the field of “Energy and buildings”, the EU-SILC and HBS datasets are used in studies related to energy poverty and the housing market.

The literature is still exploring different definitions for the term “energy poverty”, as discussed by the authors in (Moore 2012). In this context, the use of EU-SILC enables delivering information according to the “consensual approach”, for example, by assessing the indicators of the inability to keep the dwelling warm (in winter) or cool (in summer). In a study about energy poverty in Greece (Papada and Kaliampakos 2016), the authors conducted a primary survey with households on objective and subjective indicators. They compared the survey results with statistical evidence based on EU-SILC information “inability to keep home adequately warm” and “arrears on energy bills and health problems”. As a final conclusion, the authors argue that energy poverty is a multidimensional issue, and using a single indicator cannot effectively capture the overall problem.

Reporting on the housing markets in EU countries is another field where the EU-SILC was used (Dol and Haffner 2010)(Eurostat 2015)(WHO 2000)(Karpinska and Śmiech 2020). Understanding the housing situation can support the formulation of different strategies to increase the retrofitting rates, thus improving building energy efficiency and climate neutrality. Owner-occupied single-family households have a more independent process of deciding if a retrofitting will be performed (or not). While in multi-family houses, the decision process requires a common consensus between different parties, which in many cases is not easily achieved, making it the first barrier to overcome. Additionally, other barriers are the tenant/owner dilemma and the question of how the renovation costs will be divided between the parties. In social housing, aspects such as reallocation during the retrofitting process and government investment are also relevant topics in retrofitting.

2.3.4 Literature using HBS

The literature review identified fewer studies using HBS data when compared to those using EU-SILC, showing a potential for more scientific exploration. Using HBS data, Camboni et al. mapped fuel poverty in Italy (Camboni et al. 2021). In this paper, statistical matching was carried out using energy performance certificates (EPCs), census and HBS data at the municipal level. The authors argue that the risk of fuel poverty is increased by the energy inefficiency of the home, the size of the home in relation to the household size and the lower total household expenditure. Therefore, by matching the datasets and mapping different households, they hoped to support the effective design of policies and tackle energy poverty issues.

2.3.5 Literature matching EU-SILC and HBS

Two papers have been identified that deal with the statistical matching of EU-SILC and HBS and have a stronger focus on socio-economic aspects. In one of these studies, Donatiello et al. (Donatiello et al. 2014) evaluate the possibility of matching the variables of households' income and consumption in Italy using EU-SILC and HBS for the reference year 2011. The same paper applies a non-parametric (random hot deck) method to impute the variable "expenditure" from the HBS into the EU-SILC dataset. The results showed a correlation between income and class of expenditure. In another study, Serafino and Tonkin (Serafino and Tonkin 2017) imputed HBS data on income into the EU-SILC dataset to study material deprivation from EU-SILC for six EU countries: Belgium, Germany, Spain, Austria, Finland and the UK. Although the EU-SILC data has information on income, the authors aimed to compare both SILC and HBS, as HBS was considered to be more reliable. The study focuses on the methodological approach and compares three different matching methods. The main conclusion was that the mixed method (using both non-parametric and parametric methods) performed slightly better than the other methods.

Both studies have in common that the HBS is the donor dataset, and the interest variable is the household expenditure. The novelty of the present paper is, firstly, that the HBS is the recipient dataset, and EU-SILC is the donor of the variable "dwelling type". By using the HBS as the recipient, the indicator "saving" and the numerical quantification of household energy expenditures can be calculated. More explanations about the difference between donor and recipient datasets are presented in Chapter 2.3.1.

3 Defining Staged Retrofits

This chapter presents the concept of the Staged retrofits approach from different perspectives. Chapter 3.1 discusses the existing terminologies. Chapter 3.2 presents the historical evidence of potential triggers for staged retrofits. Chapter 3.3 presents the differences between single-stage and staged retrofits. Chapter 3.4 presents a deterministic analysis of how to automatically allocate difference measures to develop a building roadmap (a simplification for modelling purpose). Finally, Chapter 3.5 presents the related policy elements existing in the EPBD.

3.1 Discussion about the terminology

The EPBD introduces policy instruments and elements and provides terms and definitions related to the energy performance of buildings. However, these terms and definitions are sometimes not specific enough. Therefore, the recast is vital to improve clarity on them. This is specifically the case for the terms “step-by-step” and “renovation”, and this chapter explains ambiguities in the terminology related to building renovation activities from a policy and technical perspective.

“Renovation” is the renewal or repair of a building. However, the performance of this activity in terms of “depth” (meaning energy or CO_2 emission savings) is not directly implicated in the term. In a study about renovation activities and their energy performance in the Dutch residential building stock (Filippidou, Nieboer, and Visscher 2017), the authors noted the need for packages for high energy savings measures rather than single refurbishment measures. “Refurbishment” means an improvement by cleaning, decorating and re-equipping, and often has a more aesthetic purpose. The policymakers recognised the need for being more specific in the definition and introduced in the EPBD the terms “deep renovation” and “major renovation”. However, experts still work to formulate a more specific definition, and since the beginning of work on the present thesis in 2017, the definition of both terms was still under development. With the current ongoing EPBD review proposal, the following definitions are proposed (European Commission 2021):

> “***Deep renovation***: *means a renovation which transforms a building or building unit*
>
> > *(a) before 1 January 2030, into a nearly zero-energy building;*
> > *(b) as of 1 January 2030, into a zero-emission building;*
>
> ***Major renovation***: *means the renovation of a building where:*
>
> > *(a) the total cost of the renovation relating to the building envelope or the technical building systems is higher than 25 % of the value of the building, excluding the value of the land upon which the building is situated; or*
> > *(b) more than 25 % of the surface of the building envelope undergoes renovation; Member States may choose to apply option (a) or (b)*”

The term “retrofit” is commonly used to indicate an improvement in a building’s energy efficiency and sustainability aspects. Although this term is not mentioned in the EPBD, a literature review of modelling approaches (presented in Chapter 3.2) confirmed that “retrofit” is widely used in the literature. Conclusively, “retrofit” is the most precise term to refer to a building’s activity that generates an improvement in the energy performance – therefore using, for example, energy demand and CO_2 emissions indicators to assess the depth of the activity.

The BRP brings the time perspective of renovation activities by providing long-term and step-by-step renovation roadmaps for a specific building. However, according to the literature review on modelling approaches (presented in Chapter 3.2), the studies do not explicitly mention the time when the measures should be performed, perhaps assuming that they should be performed all at once. The EPBD 2018/844/EU also mentions the term "staged" for gradual renovation. However, a more robust and clear definition was only proposed by the current ongoing EPBD proposal:

> *"**Staged deep renovation**:* means a deep renovation carried out in several steps, following the steps set out in a renovation passport in accordance with Article 10."

The main conclusions from this terminology review to denominate activities in buildings that aim to generate energy and CO_2 emissions savings and to indicate the time perspective are:

- "Staged" and "step-by-step" are synonymous terms to indicate that renovation measures are not performed at once but rather gradually (or stepwise). In 2018 the term "step-by-step" was introduced, but now "staged" is more commonly used.
- "Retrofit" is the term that indirectly means that the building renovation activity implicates energy and CO_2 emission savings, while the new definition for "deep renovation" indicates specific building targeted building standards (nearly zero-energy building or zero-emission building) in a time horizon, respectively before or until 2030.
- "Major renovation" does not provide an indication of the energy savings or CO_2 emissions targets, but rather it indicates investment costs or addresses the share of the building surface.

The literature review also identified the "sequencing" of retrofitting measures (Ibn-Mohammed 2014). The author used a decision support system model to define the sequence and the ranking of retrofitting measures for non-residential buildings. The same term, "sequencing", was also used to describe and analyse the complexity of retrofits (Murto et al. 2019). The term "phasing" was used to define the time perspective (also called as temporal dimension) of retrofit measures sequence (Merlet et al. 2022). Both terms mean that the renovation measures are performed in the same building.

Another term used is "serial renovation". Here it meant a series of renovation activities in different buildings, in the sense of upscaling and carrying out renovation activities to more buildings (for example, a building portfolio). The author Ochs. et al. analysed the feasibility of serial renovation using air heat pumps in multi-apartment buildings (Ochs et al. 2022).

In the present thesis, the thermology developed over time, according to the maturity of EPBD recast. Therefore, **"staged retrofit" and "step-by-step retrofit"** are both synonyms to nominate renovation activities that are gradually performed (in a sequence) and generate high energy and CO_2 emission savings (more than 60%). In the present work, different targeted building standards are assessed (not exclusively nearly zero-energy or zero-emission).

3.2 Historical evidence and potential triggers for staged retrofits

Although the academic studies on retrofit modelling (as presented in Chapter 3.2) have focused on single-stage renovation, evidence from Germany shows that in real-life practices, the staged approach is the primarily performed one, as will be discussed next.

Fehlhaber showed the share of capital volume (in Billion Euro) invested in repair and refurbishment activities in the German building stock (residential, commercial, and public buildings) (Fehlhaber 2017). Figure 8 shows that 75% of the whole refurbishment activities are done partially, especially in the residential sector, where it represents 87%. The term "partial refurbishment" in this study refers to the fact that part of the building is renovated or any repair activity is performed. No information is provided about the energy efficiency of the measures and the depth of energy savings achieved.

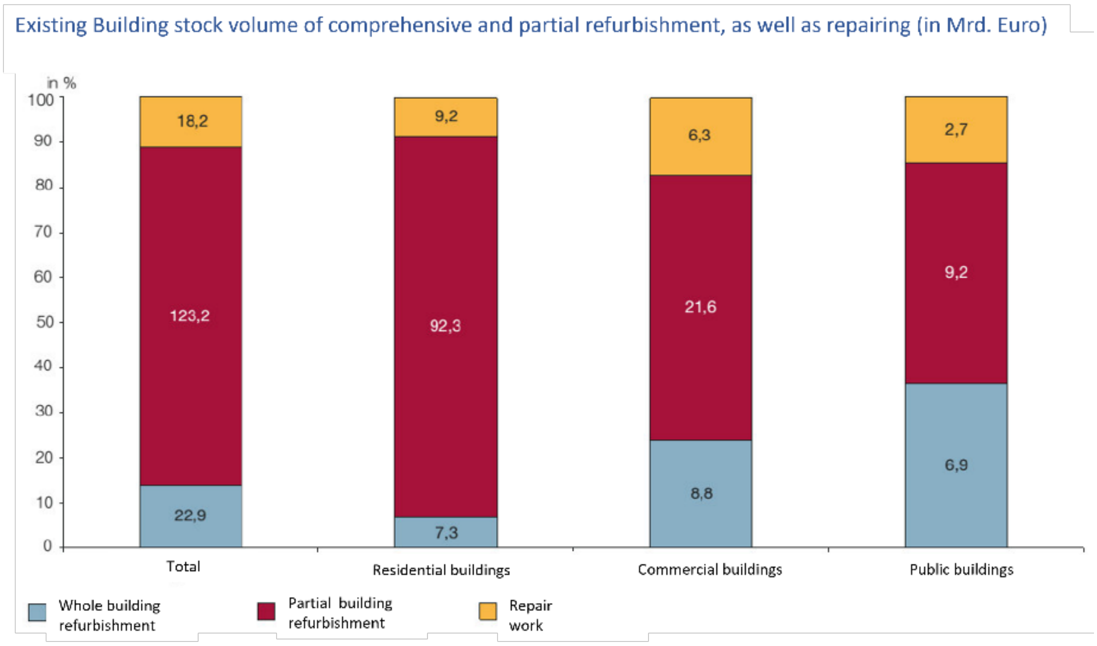


Figure 8: Investments in renovation activities in Germany. Source: (Fehlhaber 2017)

A detailed analysis with almost 7510 households was carried out with primarily residential buildings to analyse the renovation activities in the German building stock (D. N. Diefenbach, Cischinsky, and Rodenfels 2010). The results from this study showed a diversified picture of residential building stock's energy performance standards. The study indicated many partial renovations and different energy efficiency standards of the performed measures across one building through the variety of insulation thickness of the building's element. Among other results, the authors showed the percentage of insulation per building element (walls, roof or upper floor ceiling, cellar ceilings, or floor) for different construction periods and the distribution of various insulation thicknesses installed in the buildings.

Regarding the heating systems, the study showed the distribution of different heating technologies. A relevant finding of this study is that, in many cases, the renovation measures were performed at different times – serving as statistical evidence that partial renovation is commonly performed in actual buildings. It was also shown that many renovation cases did not comply with the energy efficiency standards in force at the time. This study alerted to the emerging danger of not achieving building stock decarbonization targets in Germany due to the low rates of deep renovation.

Some years later, the same authors repeated a similar approach to the previous one to actualize the data (Cischinsky and Diefenbach 2018). This second study explicitly proved that most renovation activities were done partially stead of at once and showed the different renovation rates for each building element – between 2010 and 2016: 1.8%/yr windows and glazing replacement; 1.5%/yr roof or upper floor ceiling; 0.8%/yr facade, and 0.4%/yr floor and cellar ceiling (Table 2). Regarding the heating system's replacement, the identified rates were 3 %/yr.

Table 2: Annual renovation rate mean per building element for all buildings and buildings constructed until 1978 in Germany. Source: [31]

	Mean annual modernization rates for thermal insulation (without basis weight)			
	External wall	Roof/Upper ceiling	Floor/Cellar ceiling	Windows
	All buildings			
2010–2012	1,34 % +/- 0,12 %	1,86 % +/- 0,16 %	0,72% +/- 0,24%	3,31% +/- 0,20%
2013–2015	0,84 % +/- 0,08 %	1,77 % +/- 0,14 %	0,38% +/- 0,06%	3,68% +/- 0,19%
2010–2015	1,09 % +/- 0,08 %	1,82 % +/- 0,12 %	0,55% +/- 0,12%	3,49% +/- 0,15%
2010–2016*	0,98 % +/- 0,07 %	1,72 % +/- 0,11 %	0,50% +/- 0,09%	3,46% +/- 0,14%
	Old buildings, construction until 1978			
2010–2012	1,86 % +/- 0,19 %	2,58 % +/- 0,24 %	1,05% +/- 0,36%	4,28% +/- 0,28%
2013–2015	1,1 % +/- 0,12 %	2,46 % +/- 0,22 %	0,51% +/- 0,09%	4,53% +/- 0,27%
2010–2015	1,48 % +/- 0,12 %	2,52 % +/- 0,18 %	0,78% +/- 0,17%	4,4% +/- 0,21%
2010–2016*	1,34 % +/- 0,11 %	2,38 % +/- 0,17 %	0,69% +/- 0,14%	4,29% +/- 0,19%

There are several motivations to induce a building retrofit, which are not necessarily linked to saving energy (EST 2011). They are also called trigger points and can have economic, technological and/or personal-individual reasons, for example, a heritage gain, a boiler breakdown, or even a human life cycles event such as retirement, marriage or a new home. The triggers can be seen as an opportunity to improve the energy efficiency of the home, as building owners are more likely to undertake renovation work (Fawcett and Killip 2014). Next, triggers such as building materials' lifetime and energy prices are discussed.

Different from in new building construction, in a retrofitting project, the material lifetime can be a technical trigger. During a building's life cycle, maintenance and operation activities constantly happen to avoid the first stages of degradation and failure of building elements (Flores-Colen and de Brito 2010). These activities can be induced by unpredictable damages, such as breaks, leakages and cracks, or predictable parameters, such as the material's durability, which defines the material's lifetime. In a study about factors influencing German house owners' preferences on energy retrofits, the authors (Achtnicht and Madlener 2014) concluded that most homeowners have a rational behaviour to wait until building components end of their useful life before approaching renovation or replacement.

The Russian-Ukraine war worsened the climate and energy crises, as it generated an energy security problem due to the significant and rapid increase in energy prices. Consequently, it also generated a demand for carrying out measures to reduce the dependency on natural gas and oil from potentially unstable and undemocratic countries or regions (i.e. Russia/Ukraine). At the same time, deep renovation activities are recognized as one of the key action points against this dependency because they have the potential to reduce building energy demand.

Maia et al. analysed the share of natural gas expenditures and discussed if energy prices increase were possible triggers for retrofitting for the Spain 2015 data (I. E. N. Maia et al. 2023). The paper concluded that energy security might be a trigger for retrofitting activities; however not necessarily driven by higher energy prices. Also, the low budget restrictions for certain groups showed that innovative financing schemes and incentives are still needed.

3.3 Single-stage versus staged retrofit

Fawcett researched the time dimension of different renovation approaches based on empirical evidence of low carbon retrofits in the UK and identified that some retrofitting activities occurred over time, contrary to others that happened at once (Fawcett 2014). Mainly there are two main approaches when referring to the time perspective when retrofitting measures are carried out:

a) single-stage (or all measures at once): whole house and envelope-first
b) staged (or over time): room-by-room, measure-by-measure and step-by-step

The main critical point against a staged approach by some building energy experts is that satisfactory energy savings are often not achieved. Mainly, as soon as the single-stage retrofit is performed, energy savings can be achieved faster than in the staged approach. In the single-stage approach, besides a significant reduction in the heat losses through the building's surface, it also avoids the oversizing of the installed heating system, which compromises its efficiency. In the staged approach, there is a high risk of interruption due to a lack of financial means, lack of technical knowledge, building owner change etc. And then, all necessary measures are not entirely carried out. Table 3 compares both approaches, single-stage and staged, according to different techno and socio-economic criteria: time dimension, effects on climate targets, risks, barriers, material costs, labour and montage costs and disruption and re-allocation.

Table 3: Retrofitting approach comparison. Source: own-illustration based on (Topouzi et al. 2019)

Criterion	Single-stage	Staged
Definition	Only major renovation (including the whole building envelope)	Retrofit measures performed according to trigger points.
Time dimension	At once	Over years (or decades)
Effects on climate targets	Fast CO2 emission reduction (potentially more energy savings)	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.
Main barriers	Disruption and/or affordability	Less information about correct sequence of measures
Material costs	At once – the possibility that loans and incentives are available	Cost-shifting – further measures costs can be partially anticipated
Labor / Montage Costs	At once	Scaffolds and other construction site equipment might have to be mounted more than once
Disruption and re-allocation	Probably the building occupants will have to be re-allocated outside of the house or apartment during the work. This may generate additional renting costs (in other places)	Allows for re-allocation in between the house or apartment, without the need leaving the place

Commonly performed measures are insulating building elements, external walls, roof (or top floor ceiling) and floor, replacing windows, and replacing the active system (heating, cooling, ventilation, lighting and domestic hot water). While in the single stage, all the measures are performed at once, in the staged approach, a stage consists of one measure or a combination of measures. 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. Then, in the staged approach following aspects become more relevant (more details about that can be seen in the section below):

- **Number of stages (or steps):** while in the single stage, the number of steps is one (meaning that the renovation is performed at once), in the staged renovation, it can vary. Then, after discussing with different stakeholders and experts, the number of a maximum of three is considered plausible, being extendable until five stages for a staged renovation.
- **Allocation (or combination) of measures (in a stage)**: this aspect is especially relevant when performing and implementing the measures, as it should avoid lock-in effects and also take into account technical specificities and scaffold costs. The replacement of each technical system or the retrofit of each building element can be seen as a stage. But also, different measures can be combined in a stage where, again, varied numbers of measures packages are possible. However, the higher the number of packages, the longer the time for considerably achieving energy savings and the higher risk of interruption.
- **Sequence of the stages**: together with the combination and allocation of different measures in a stage, also the sequence when each stage is performed has to be defined. The sequence basically defines the order in which each stage will be performed.

3.4 Deterministic analysis of roadmaps: allocation of measures per stages

This chapter presents a deterministic analysis of how possible measures can be combined and allocated in different stages to generate plausible roadmaps simplification. These simplifications are sufficient for the simulation and modelling proposed. As the main result, simplified roadmaps with a reduced probability of lock-in effects were developed (Figure 9).

The building roadmap consists of a specific plan that contains information about which measures should be performed, when and with which combination and their energy efficiency standard. In real life, a building roadmap should also consider individual context and preferences, and long-term perspective, also called an individual building renovation roadmap (IBRR). Also, an on-site visit by a building expert may be necessary (Fabbri, Volt, and de Groote 2018a; I. Maia, Kranzl, et al. 2020).

In the staged approach, not only the energy efficiency standard but also the combination of the measures and allocation per stage is relevant. The allocation of measures requests a deeper understanding of the technical implementation requirements of each measure; this means which measures can/should be combined (or not) and which dependencies exist between them. The main intention behind that is to avoid lock-in effects. Lock-in effects happen when specific energy savings are not achieved, and due to some circumstances, it cannot be quickly changed, remaining for many years less energy efficient. Consequently, losing the opportunity to have maximised energy efficiency savings. A practical example is: due to a specific short length of a roof overhang; the exterior wall insulation thickness has to be limited. In this case, it is better to first extend the roof overhang during the roof renovation. Otherwise, the wall insulation (at a later stage) would not be possible without an extra, costly measure at the roof again. A deterministic analysis explored the allocation of possible renovation measures based on the literature (BMWi 2017), (Monteiro and Fragoso 2018) (fit-to-nZEB 2017). Table 4 presents the summary of the technical description presented next. It includes, for each measure, the different trigger points to perform renovation activities in buildings. Then, the technical energy efficiency implementation and the dependent measure.

In general, a building envelope has the main function of protecting the building interior against bad weather conditions. Being the prevention of building material’s exhaustion, a trigger point to avoid or repair any damage. In the case of the façades (or external walls), a common trigger point is renewing the plaster layer. The façade normally has a higher surface area and is connected to other building elements, particularly windows and roofs (see Table 4: Façade or external wall).

In the praxis, the roofs’ retrofits are complex work and require special care from the point of view of building physics and craftsmanship. If the attic space is not regularly used as a heated space, the upper ceiling insulation might be sufficient to provide satisfactory energy efficiency savings. Different from roof insulation, upper ceiling insulation has no dependency on other measures (see Table 4: Upper Ceiling and Roof).

Many old buildings have one-glazing windows, which are significantly less energy efficient. Therefore, replacing them with multi-glazing windows can generate significant energy savings. Ideally, it should be combined with the insulation of the façade to ensure that the windows sit in the right place on the insulation. This decision will also depend on the fact if the façade is insulated or not (and have an acceptable energy performance). Together with the glazing improvement, other measures that increase the air-tightness (sealing the window frame) should be performed. And installing exterior sun shading is important, especially in climates with high solar radiation (see Table 4: Windows).

An insulation layer can be added to the floor above the floor plate or below the cellar ceiling expensive (see Table 4: Floor and Cellar ceiling). The latest may generate less disruption and is the most adequate one if the cellar room height is high enough and the cellar ceiling construction allows it to do so (not the case in arced ceilings). All measures done in the cellar should be done at the same time. This may include the heating system replacement. This measure is often performed independently from other measures due to the short service lifetime. By replacing the heating generation system, it is important that the right dimension is assured. Otherwise, the over-dimensioned system will work inefficiently. This can happen if the heating system is replaced before other envelope measures are performed. That is the reason why many experts suggest first performing the envelope measures and then replacing the heating system. The choice of the new system can depend on the energy carrier, energy efficiency, investment costs and energy prices over the use phase. With the introduction of CO_2 emissions taxes or the increase in energy prices, the operation of non-renewable heating generation systems will become more expensive (see Table 4: Heating system generation).

Not only the heating generation but also emission, distribution and control systems have an influence on energy efficiency (see Table 4: Heating distribution system). Low-temperature heating systems request the installation of an adequate emission system, for example, a radiant floor. While in high-temperature systems, radiators are the most commonly installed emission system. Also, well-functioning pumps and pipes are necessary. A demand-side measure is the installation of thermostats. This measure enables the building user to better adjust the room temperature, which also generates energy savings as the user can adapt it to the room occupancy. This measure is easily performed and independent from any others (see Table 4: Heating system control).

The last measure considered is on-site energy generation. Commonly used technologies are thermal energy generation (with solar thermal panels) or electricity generation (with PV cells). Possible combinations are installing PV with heat pumps, as the first generates electrical energy and the second electricity-based heat generator. In a similar way, the combination of solar thermal systems with biomass boilers is possible. The installation of solar thermal panels is more broadly used in hot climate countries with high solar radiation for heating domestic hot water. In general, this measure can be combined with the implementation on the roof or independently (see Table 4: Renewable energy generation).

Table 4: Technical trigger points and possible dependent measures

Building element and component	Trigger point	Technical energy efficient implementation	Other dependent measures
Façade (or external wall)	Renew of plaster due to bad conditions	Improving the energy efficiency by adding or changing the insulation layer	Windows replace and/or
			Roof renovation as the right connection with roof overhang is needed
Upper ceiling	Not identified	Improve the energy efficiency by adding or changing the insulation layer	Different from roof, this measure is not dependent on the facade
Roof	Renew of roof due to bad conditions	Improve the energy efficiency by adding or changing the insulation layer	Insulation of the roof can be coupled with a new roofing or with a roof extension.
			Façade insulation as the right connection with roof overhang is needed
Windows	Broken glass, a defect in the mechanics or weather-related damage	Improving the energy efficiency by replacing the windows	Improving air-tightness
			Façade renovation
			Exterior sun shading
Floor	Interior refurbishment	Improving the energy efficiency by adding or changing the insulation layer	No energy efficiency measure in the envelope is directly connected. However, this is more complex then insulating the cellar ceiling.
Cellar ceiling	Improvements in the cellar, as for example in the technical systems	Improving the energy efficiency by adding or changing the insulation layer	Improvements in the heating system as heating system replacement or insulation of the heat distribution pipes
Heating system generation	Age, state of preservation or energy efficiency of the equipment	Improving the energy efficiency by replacing the equipment	The replacement of the heating system is independent of any other measure. That is the most measure performed as single measure (in the praxis)
Heating distribution system	Age of pipes, connection of a new pipe or not functioning line routing	Improving the energy efficiency by insulating the pipes and repairing the system	Replacement of the generation heating system Change of the role heating system (from high to low temperature system)
Heating system control	No thermostat in the rooms	Improving the energy efficiency by allowing building users to regulate the room temperature	Adjust the heating system hydraulic circulation, if necessary
Renewable energy generation	Any of the situations mentioned, or if the building does not have a RES system	Supply the building renewable energy, produced on-site or not	Depend on the heat generation system chosen, available roof area and domestic hot water demand.

Figure 9 explores different possibilities of roadmaps and considers different numbers of steps in a roadmap, considering the technical specifications according to Table 4. A roadmap with five or more steps seems technically not possible as it would increase the chances of lock-in effects, being a maximum of four steps ideal. The sequence when each step should be implemented can also be determined deterministic. In the present thesis, the sequence is defined by the optimisation model that calculates the optimum timing when each stage should be performed. The sequence is treated as a constraint and can be pre-defined or not.

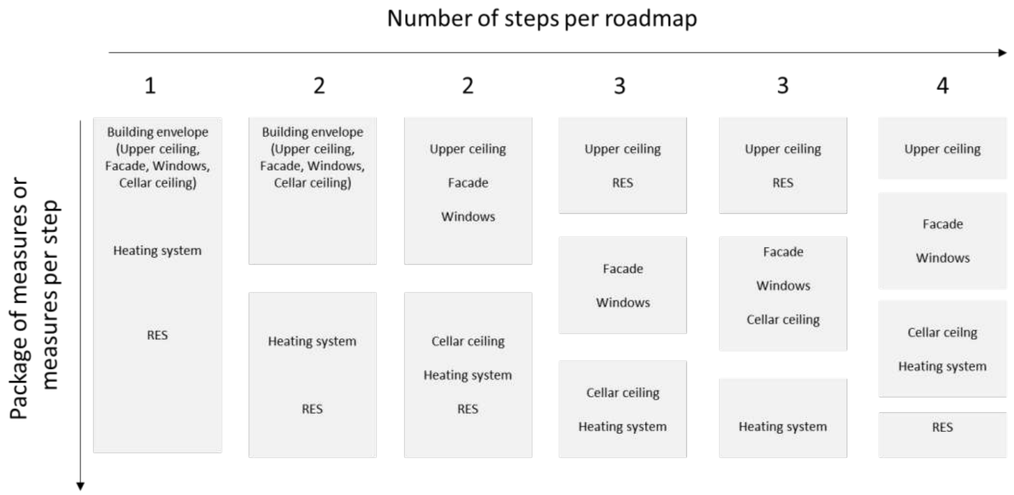


Figure 9: Different roadmap variants in terms of the number of steps and possible combination of measures per step (for an individual building)

3.5 Related policy elements existing in the EPBD

The EPBD, together with the EED, are the main legislative instruments that aim to promote the increase of EU building stock energy efficiency. The first version of the EPBD was published in 2002 (Directive 2002/91/EC), followed by the recasts in 2010 and 2018 (EPB 2020). Currently, another recast is under negotiation (European Commission 2021).

2018 the EPBD introduced in Article 19a the voluntary renovation passports – also known as "building renovation passports" (BRP). Sesana and Salvalai reviewed the concept of BRP, presenting its potentialities and barriers (Sesana and Salvalai 2018). The authors highlight the prime role of BRPs, which is to help overcome the building information imbalance between different stakeholders: building owners, public authorities, financing institutions, providers of mortgage credit, investors and insurers, construction companies, stallers and real estate companies. BRPs should improve building-related documentation and information that enable a proper assessment of the overall building quality, energy efficiency and CO_2 emission. With that, the BRPs bring the existing buildings into focus and trigger renovation activities. From the perspective of building owners, the BRPs should also help and support in planning a staged renovation of their building, therefore serving as a complementary document that provides a long-term and staged renovation roadmap for a specific building. From the perspective of finance institutions, according to the same authors, by increasing the building-related information, investment risks can be better calculated and consequently reduced. Finally, the authors concluded that for developing BRPs following aspects should be taken into account: i) long-term perspective; ii) timing and sequencing of actions developed; iii) customer engagement and consideration of the individual renovation context; iv) attractiveness and motivation; and v) automation and dynamism of the process instead of a static tool. In the present thesis, the first two points are closely studied.

In Europe, there are already some examples from real-life practice which focus on the key concept of building passports as an initiative to increase awareness about a building`s energy performance and to encourage homeowners to conduct deep-staged renovations. One example is the concept of renovation roadmap (Sanierungsfahrplan – SFP) in Germany, which was launched in 2015 as an energy audit instrument (Baden-Württemberg 2015). In France, the roadmap Passeport Efficacité Énergétique (P2E) provides a set of solutions ("performance combinations") which enable the building to reach low energy or n-ZEB levels (P2E 2018). In Flanders (Belgium), the "De Woningpas" is a digital, online tool that allows the storage of building-related information and calculates automated renovation information (Flanders 2017). In this context, Sesana and Salvalai present an overview comparison between these initiatives considering the following criteria: objective, content (format, logbook, graphic design, geo-localization and climatic data, building typology, performance indicators, comfort), initiators (model of development, financial scheme base information) and development process (on-site audit, building owners, stakeholders' engagement, political support, training). The same study also lists the performance indicators in a BRP, making evident the holistic intention: energy consumption, thermal comfort, airtightness and ventilation, indoor air quality, noise insulation, lighting (natural or artificial) and CO_2 emission. These indicators go beyond the indicators on the EPCs that are the currently used instrument to assess the energy performance of buildings; however, they do not yet include other indicators.

The H2020 EU-funded project iBRoad (Individual Building Renovation Roadmap) had a strong focus on the concept of BRPs and worked on eliminating the barriers between house owners and building energy performance (iBRoad 2018). During the project, two tools were developed: the building logbook and the roadmap assistant. The building logbook (European Commission et al. 2020) has as its main functions collection and centralisation of all relevant information about a building, from administrative information (i.e. address, cadastre number) to building characteristics (i.e. U-values, surface area, energy efficiency class). The roadmap assistant is the tool that enables the development and layout of the staged renovation plan, which is, at its core, a home-improvement long-term plan which considers the occupants' needs and specific situations. During the project, the tools were tested using building-related data and a roadmap developed by energy auditors. This data was used in the present thesis during the development and demonstration of the staged retrofit optimisation model (see details under 5.2.2).

The H2020 EU-funded project ALDREN (Alliance for Deep Renovation in Buildings) had the main focus of targeting and supporting investments in deep renovations (Aldren 2018). For that, the project proposed an EU-wide building assessment framework that included the use of sustainability metrics in certification schemes and the use of decision-support protocols and tools. In this context, the ALDREN BRP was developed as a dynamic instrument to be used during the whole renovation path. Like the iBROAD project, the ALDREN project also developed a logbook, "LogBook", and a renovation roadmap ", RenoMap" (with one or multiple stages).

The H2020 EU-funded project RenovEU developed a tool that allows the user to roughly calculate the energy consumption of a building (RenovEU 2022). The tool also offers improvement options for energy savings and increased comfort to meet certain incentive requirements. Then, the principle of staged retrofits and the BRP is also applied in this project.

Gomez-Gil et. Al. evaluated the technical operability between existing national data sources in Italy and Spain and BRPs, with the main objective of verifying to which extent the data sources can be used to populate the future Building Logbooks (Gómez-Gil et al. 2023). The authors concluded that there are still limitations to making the operability between different data sources feasible in practice. Besides technical aspects, also legal data protection (GPR) are a known barrier. Nevertheless, the study highlights the relevance of matching data sources to obtain holistic building and building user information.

The next recast is being formulated to line the EPBD with the Renovation Wave Strategy published in 2021 by the EU Commission and part of the European Green Deal (European Commission 2020). The Renovation Wave focuses on three areas: tackling energy poverty and the worst-performing buildings, renovating public buildings and social infrastructure, and decarbonising heating and cooling systems. An important aspect is that the Renovation Wave builds on the national LTRSs (among other national plans) that specify the EU Member States' policies and actions to achieve their climate targets (European Commission 2019) (Staniaszek, Kockat and Vitali Roscini 2020). The LTRSs are underpinned by a financial component where the direct investment areas are defined (more details in Appendix IV). Figure 10 presents the main suggested measures in the new EPBD revision proposal 2021:

Measures to increase the number of buildings being renovated and renovation depth	Minimum energy performance standards (MEPs)
	Building renovation passports (BRP)
	Energy performance certificates (EPC) strengthen quality and comparability.
	Deep renovation standard
	Long-term renovation strategies (LTRS)
Options to enable decarbonisation of new and existing buildings	Introduction of a definition of 'zero-emission buildings' (ZEB)
	Increase the scope of information and coverage of energy performance certificates (EPCs)
Measures to increase the modernization and quality of buildings and their systems, enabled by the digitalisation of information tools	Measures to remove building-related barriers to e-mobility
	Enhance the role of EPCs as digital tools
	Measure to support the implementation of the smart readiness indicator (SRI)

Figure 10: EPBD proposal 2021 – summary of measures per policy area. Source: (European Parliament 2022)

Recently the EPBD proposal 2021 included a clearer definition for staged renovation (in the EPBD recast from 2018): "a solution to address the issues of high upfront costs and hassle for the inhabitants that may occur when renovating in one go" (European Parliament 2018). With that, the EU Commission recognizes the real-life barriers to undertaking single-stage renovations and legitimizes the staged renovation as a solution for that. Consequently, encouraging more scientific work that should support policymakers in setting the appropriate framework conditions. In this context, it is important to note that the directive mention "staged renovation" and not "staged retrofit", leaving the energy efficiency depth still open when associated with the practice. According to Figure 10, in the new EPBD proposal, the "deep renovation standard" is a separate topic.

4 Data, Method and Limitations

Figure 11 shows the overview of the methods applied to answer the three research questions presented in Chapter 1.2 and how they interact with each other, which means how the outcomes from one study were used in other studies.

Method 1 (M1) was developed to answer the following *Research question 1* (**RQ1**) "*How can existing datasets (HBS, EU-SILC) be merged to generate techno-socio-economic datasets and to provide household-specific insights about building retrofitting triggers?"* Then, a workflow for the statistical matching was developed and tested to merge both datasets, including data preparation, datasets comparison and modelling. The model consists of a logistic regression to impute the categorical variable "dwelling type" into the HBS data, and the implementation was done using the free software R for statistical analysis. There were three main outcomes from this method: 1) the quantification of the following variables natural gas expenditures, savings (representing household's budget restrictions) and income for each of four household types owner-occupied and rented for both single-family houses and multi-family houses. 2) The households' types according to dwelling type and ownership status also made clear that the triggers for renovation vary according to each type. According to this finding, it was decided to develop an optimisation model for a specific household type, "owner-occupied single-family house". **Method 1** is presented in more detail in Chapter 4.1, and the results in chapter 5.1.

Method 2 (M2) was developed to answer the following *Research question 2* (**RQ2**) *"For delivering the optimum timing of a staged retrofit, which techno-economic parameters should be taken into account in an optimisation model? To which parameters and variables is the model sensitive?"* The model was outlined to calculate the optimum timing when each retrofit stage should be performed in order to achieve the fastest time to perform each measure. The model developed is a mixed-integer linear programming code in Python language that uses Gurobi as a solver. The results also allow for calculating the optimum total time needed to complete all stages of a building roadmap, enabling the comparison with the single-stage approach. **Method 2** is presented in more detail in Chapter 4.2, and the results are in Chapter 5.2.

Method 3 (M3) was outlined to answer the following *Research question 3* (**RQ3**) "*Which insights about staged retrofits and their impacts on the CO_2 emissions can be observed* when *upscaling to a building stock level?*" M3 is a direct application of the staged retrofit optimisation model developed in M2, using data-driven budget restrictions as input data that resulted from M1. Additional country-specific input data, such as building typologies, initial investment costs, and energy prices, were also used for the Spanish case study (more details presented in Chapter 4.3). Also, a case study that investigates different energy efficiency measures under a country comparison for Spain, Germany and Sweden is performed. Both results are in Chapter 5.3. Chapter 6 also answers RQ3 by presenting a case study of the impact of renovation cycles and staged retrofitting on the energy needs for space heating (case study for Germany).

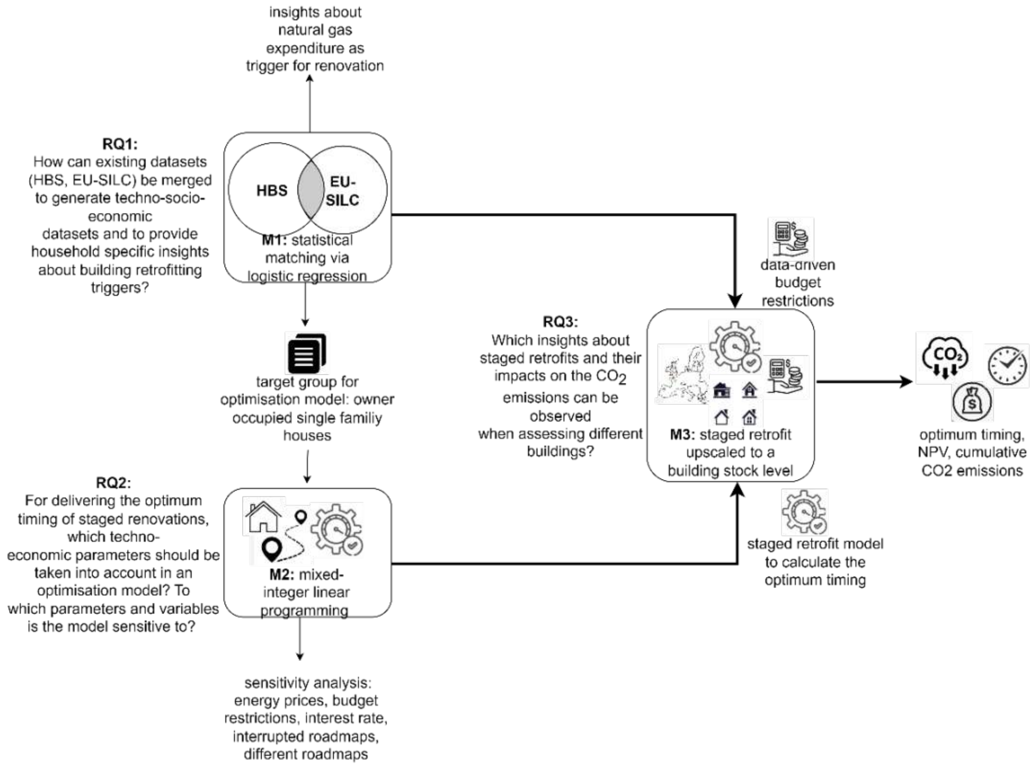


Figure 11: Overview of the thesis methodological approach

4.1 EU-SILC and HBS statistical matching using logistic regression

4.1.1 Research questions

The outline of a statistical matching methodology using EU-SILC and HBS data sources was outlined with the aim of answering the following two research questions (RQ):

RQ1: What is the replicable methodology for merging HBS and EU-SILC datasets in order to create an accurate statistical model and set up synthetic data?

RQ2: What can be learned about household annual natural gas expenditures, savings and incomes of four different household types for the case of Spain?

These RQs are part of the overarching research question RQ1 (Figure 11). To answer these questions, the EU-SILC and HBS are described in Chapter 2.3.2. The developed and tested workflow is presented in Chapter 4.1.2. Finally, the results are presented in Chapter 5.1.

4.1.2 Statistical matching workflow

Figure 12 summarizes the methodology to perform the statistical matching that consists of the following stages: 1) data preparation, 2) dataset comparison, 3) modelling and 4) results and interpretation.

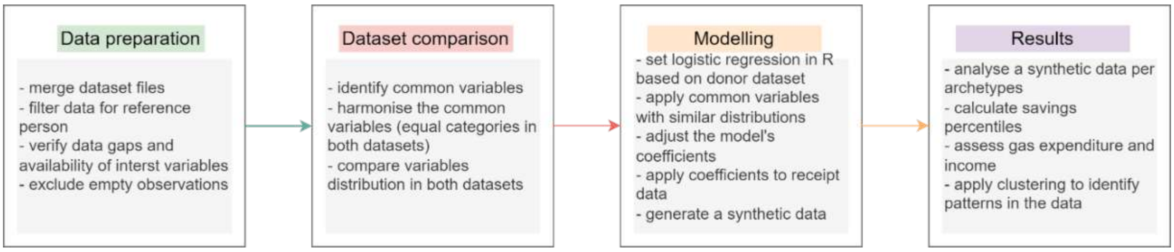


Figure 12: Statistical matching workflow overview

The tasks performed during the data are: 1) filtering data for the household reference person, 2) merging personal and household data files, 3) excluding observations with empty fields, and 4) verifying data gaps and the availability of variables. Although the survey foresees the collection of a certain variable, the data field may be empty if it was not part of the country's survey. The completeness of the data refers to the responses from the reference person or survey respondent. If the completeness is 100%, the variable was answered by all households. A maximum of 15% data gap was considered acceptable. Then, a step consisted of carrying out a comparison variable-by-variable. The pre-selected matching variables are shown in Figure 13. The last step consists of verifying if the variables were equally described and collected by the surveys. If the variables are described through similar (but not equal) categories, then a harmonisation between the categories should be done. A discrepancy lower than 10% was considered tolerable. This is a fundamental condition that enables the feasibility of a parametric approach. The results from the data preparation and comparison are presented in section 6.1.

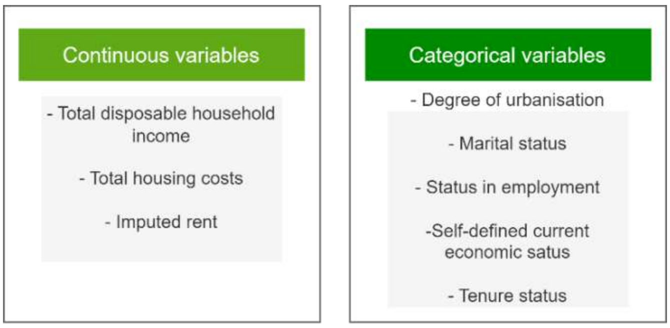


Figure 13: Pre-selected matching variables

As part of the modelling, the choice of the regression model was defined by the characteristics of the interest variable "dwelling type". As the variable dwelling type is binary, being 1 for single-family houses and 0 for multi-family houses in the EU-SILC dataset. To assess the model performance, a receiver operating characteristic (ROC) curve is a commonly used method that presents the rate of true and false positives. It also helps to determine the best "cut-off" probability value to define if an observation should be classified as 1 (is the interest category) or 0 (if not the interest category)(Mandrekar 2010). Figure 14 shows the overview of the parametric modelling divided into three stages. The modelling was implemented in R. The logistic regression model was generated after dividing the sample into training/testing data using EU-SILC data. The forecasted and actual values were compared to estimate the model’s forecasting accuracy and ROC curve (stage I). Then, the next stage consisted of applying the same model but using HBS data to predict the interest variable. For successful matching, the coefficients of both models have to be equal. Therefore, as part of this stage, some adjustments can be performed by adding a residual to obtain similar coefficients (β) on the data before the final coefficients are estimated (stage II) (Moriarity and Scheuren 2001). When the coefficients are adjusted, the final matching model can be used (stage III).

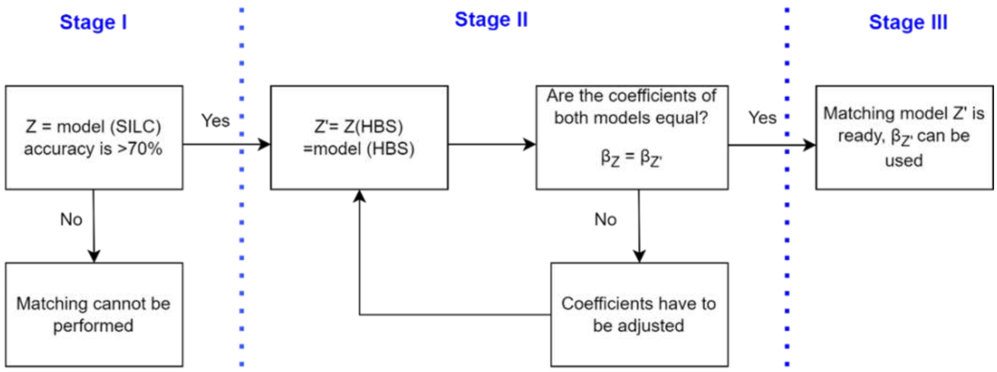


Figure 14: Overview of parametric modelling. Source: own illustration

The model delivered the coefficients to predict the variable “dwelling type” in the HBS dataset, where an imputation process was performed. Equation 1 presents the general regression equation based on the predictive approach of the conditional independence model(Harrell, 2015b):

Considering data set A with n_A observations:

$$Z_a = \beta_X X_a + \ _a ; \ a = 1, \ldots , n_A$$

Equation 1

The main goal is to estimate values for Z by applying these coefficients () to the X values in dataset A with the total number of observations n_A. The random residual is represented by e_a.

The variable of interest, “dwelling type”, is a categorical variable in the survey and was modelled as a binary, meaning that 1 is a single-family house and 0 is an apartment (or other building type). It is represented in Equation 1 as Z. Because of this characteristic of the variable of interest, a logistic regression must be used instead of a linear regression (where normally continuous variables are modelled).

$$\frac{\log \mathrm{p}}{(1-\mathrm{p})} = ß_0 + ß_1 * \mathrm{x}_1 + ß_2 * \mathrm{x}_2 + ß_3 * \mathrm{x}_3 + \cdots ß_6 * \mathrm{x}_6 + e$$

Equation 2

The results forecasted with the logistic function show the probability (p) that an observation i with x characteristics has Z = 1. By rewriting Equation 2, the logistic regression model becomes then:

$$p(Zi = 1) = \frac{exp^{ß_0+ß_1*x_1+ß_2*x_2+ß_3*x_3+\cdots ß_6*x_6+e}}{1+exp^{ß_0+ß_1*x_1+ß_2*x_2+ß_3*x_3+\cdots ß_6*x_6+e}}$$

Equation 3

where p is the probability of being evaluated as dwelling type1=single family house and 0 = apartment. x_1 to x_6 are the matching variables: x_1=marital status (category never married); x_2= marital status (category separated/widowed); x_3 = degree of urbanisation (category intermediate); x_4 = degree of urbanisation (category sparsely); x_5 = status of employment (category employer); x_6 = ownership (category rented) and e is the regression residual. The regression coefficients (ß0, ß1, ..., ß6) are calculated using a logistic regression modelling in the software/environment for statistical computing R[1].

Then, having created the synthetic data based on the coefficients and the observations in the receipt dataset, the last step was calculating the variable "saving" and assessing the natural gas expenditure for different household types. The HBS provides information about the household income and the final expenditure on goods and services for the following categories: 1) food and non-alcoholic beverages, 2) alcoholic beverages, tobacco and narcotics, 3) clothing and footwear, 4) housing, water, electricity, natural gas and other fuels, 5) furnishing, household equipment and routine household maintenance, 6) health, 7) transport, 8) communication, 9) recreation and culture, 10) education, 11) restaurants and hotels and 12) miscellaneous goods and services. Based on these categories, household saving was delivered according to Equation 4 (based on the definition explained in (UNSC 2009)):

$$saving = net\ income\ - \sum_1^n \text{expenditures}$$

Equation 4

where expenditure (euro/yr) includes the n categories, 1 to 12, above.

4.2 Outlining a staged renovation optimisation model

4.2.1 Research questions

Firstly, the work adds to the existing literature by outlining a framework for staged retrofitting optimisation modelling. It specifically does this by creating more comprehensive modelling for a step-by-step retrofit approach. Secondly, it takes into account the homeowner's budget restrictions to invest in renovation.

The staged retrofit optimisation model was outlined with the aim of answering the following three research questions (RQ) as part of the overarching research question RQ2 (in Figure 11):

[1] Online accessible under https://eeg.tuwien.ac.at/gitlab/ina/logistic-regression-statisticalmatching

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?

4.2.2 Real life building renovation roadmaps

In Europe, some demonstration projects focus on the key concept of building passports, one of which is the EU H2020 iBRoad project (iBRoad 2018). This project explored many aspects of the staged renovation concept and provided IT solutions for supporting auditors in developing a staged, long-term renovation roadmap for individual buildings, especially for owner-occupied single-family houses. The project tested the developed software tools on real buildings, which will serve as case studies in the present thesis. The project reports describe how the field test took place and evaluate the implementation of tested tools (Werle, Lempik, and Mellwig 2019) (Mellwig, Werle, and Lempik 2019). The number of stages per building roadmap, as well as the packages of measures per stage, were defined by the energy auditors. A detailed analysis of the roadmaps was performed to select five cases, which were used to demonstrate the developed optimisation model.

4.2.2.1 Pre-analysis of real-life roadmaps

A pre-analysis of the roadmaps was carried out with the aim of analysing their compliance with the national long-term renovation strategies (more details in Appendix IV: National Long-Term Renovation Strategies) and, consequently, with the EU's building stock decarbonisation strategy. This analysis provides insights into how the staged renovation approach is understood and interpreted in the practices of the energy auditor. Also, it helped the selection of roadmaps to be used when testing the model (as presented in the next section 5.2.2). During the iBRoad project testing phase, energy auditors in three different EU countries, Bulgaria, Portugal, and Poland, developed 55 real-building roadmaps while testing the iBRoad-tools. This activity included the calculation, for each building and each stage, of the building’s energy performance (current state and for each renovation stage) and CO_2 emission. This calculation was carried out with a national energy performance software, the same tool used for issuing EPCs (Energy Performance Certificates) in the mentioned countries, which follow the national standards of energy performance calculation. Table 5 summarizes the description of each tool per country.

Table 5: Description of the national energy performance calculation software

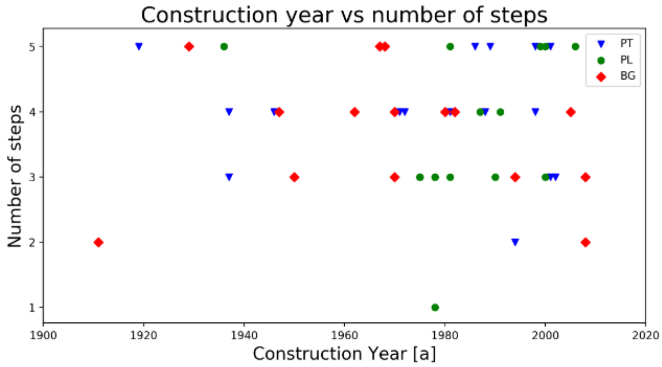
	Bulgaria	Poland	Portugal
Software for energy performance calculation	EAB Software (ENSI 2019)	Audytor OZC (Sankom 2019) or ArCADia Thermo BuildDesk Energy Certificate (Soft 2019)	National Excel spreadsheets (Itecons 2019)
Available version in English	Yes	Yes	No
Main calculation method	mainly ISO 13790:2008, adapted to Bulgaria	PN-EN 12831, PN-EN ISO 13370, PN-EN ISO 13790	Decree-Law No. 118/2013 of 20 August (republished on 23 June 2016)
Price to afford for a license	Up 140 Euro (1299 NOK)	Up 550 Euro	Up 165 Euro

Comprehensive information about the analysis is presented in Appendix II: iBRoad Roadmaps techno-economic assessment. The number of steps reflects how fast the planned energy and carbon savings can be achieved: the higher the number of steps, the longer it would take to finish performing the whole renovation plan. Although 55 buildings were tested in the project, 50 roadmaps obtained the necessary information for the present analysis. These 50 real buildings were divided as follows: 18 in Portugal (PT), 17 in Poland (PL), and 15 in Bulgaria (BG). Table 6 shows the number of stages defined by the energy auditors for each building roadmap in the countries Bulgaria (BG), Poland (PL) and Portugal (PT). In general, three, four and five stages of building roadmaps were planned.

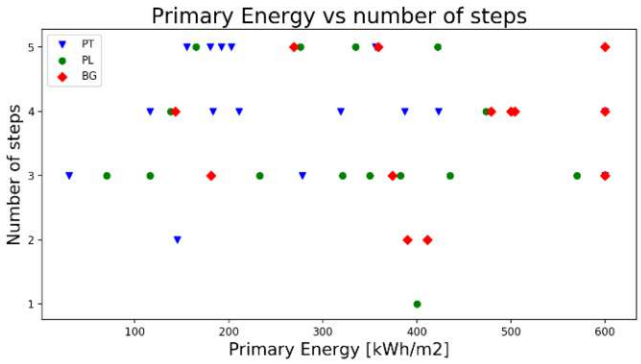
Table 6: Overview number of steps per building roadmap from each country: Bulgaria (BG), Poland (PL) and Portugal (PT)

Country	**Number of stages**					**Total**
	1	**2**	**3**	**4**	**5**	
BG	0	2	4	6	3	**15**
PL	1	0	9	2	5	**17**
PT	0	1	3	8	6	**18**
Total	**1**	**3**	**16**	**16**	**14**	**50**

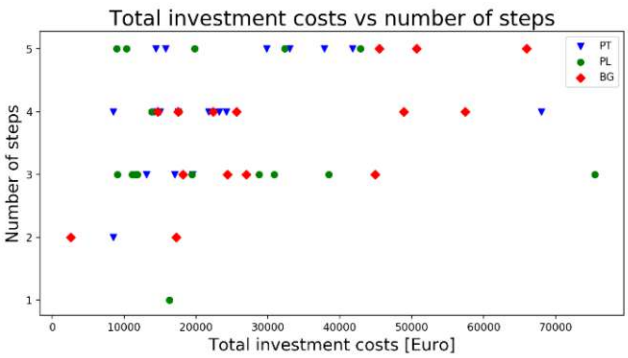
Figure 15 (a-c) shows some trends observed in the tested building roadmaps. In general, it was expected that the number of steps would increase according to the indicator: buildings with higher primary energy demand, older buildings (with older construction period) or higher investment costs would present roadmaps with more steps. However, different than expected, the graphs show no direct correlation between the described indicators and the number of steps in any of these countries. In real life, renovation activities occur building specifically, and the single solution of renovation measures are very diverse: it may be partial and vary according to the measure performed (windows, external wall etc.), and it may also vary with the depth (no insulation, middle or highly insulated buildings). Nevertheless, there is also the aspect of the heating system energy carrier, which is also dependent on the country-specific technology market and energy carriers. This generates a wide range of buildings with different construction years and primary energy demands, highlighting the individual aspect of buildings. And the need to consider the individual preferences of building owners, which makes the assessment even more complex.



(a)



(b)



(c)

Figure 15: Relation between the number of stages and different indicators (a) construction year [yr], (b) Primary energy demand [kWh/m²] and (c) initial investments [Euro]

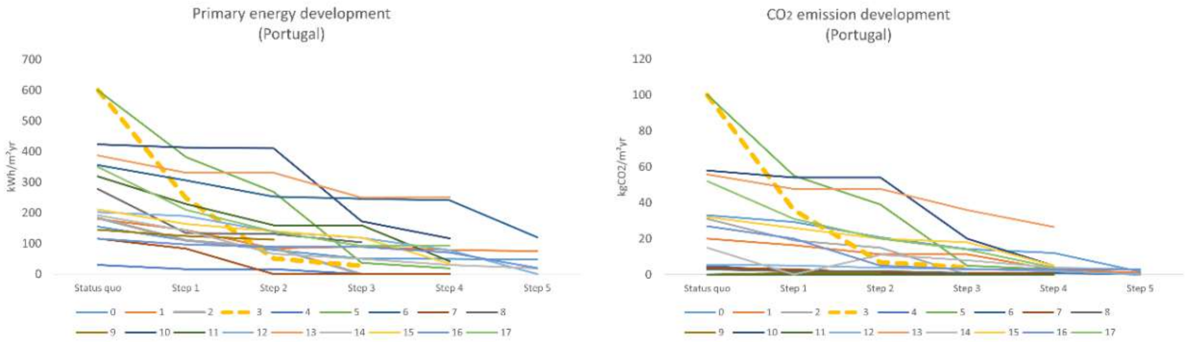
The figures above are presented:

- *Construction year versus the number of steps (Figure 15a)*: it was expected that the roadmap of older buildings would be divided into more steps. This assumption presumes that no deep renovation activity had been undertaken before.

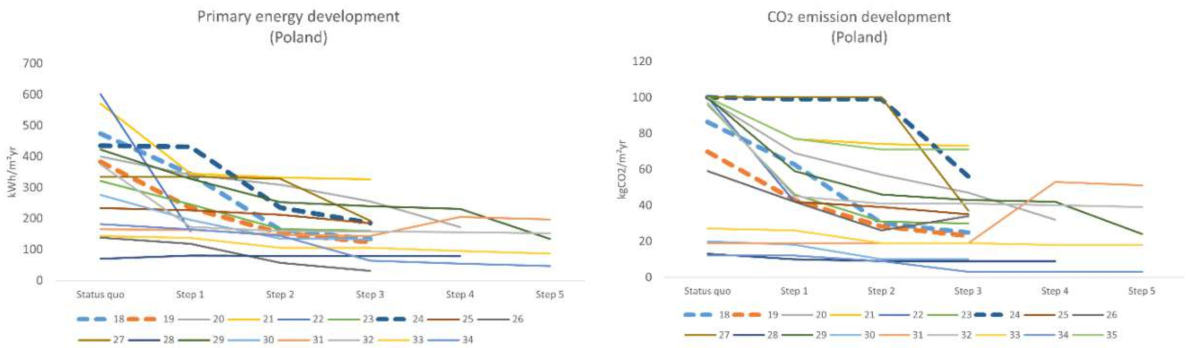
- *Primary energy versus the number of steps (Figure 15b):* similar to the indicator, it was expected that the roadmap of older buildings would be divided into more steps, assuming that more measures would be needed to be performed.
- *Total investment costs versus the number of steps (Figure 15c)*: it was expected that roadmaps with higher investments are divided into more steps to reduce the needed investment.

4.2.2.2 Selected roadmaps for testing the model

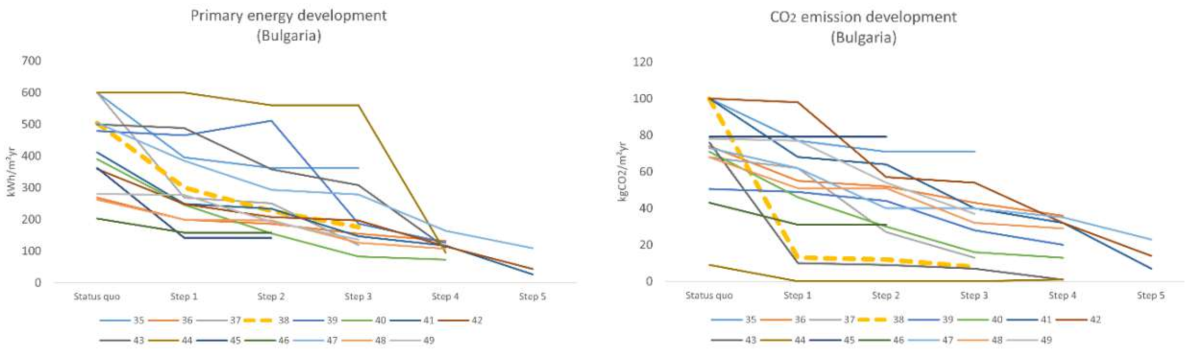
For developing, testing and demonstrating the staged retrofit optimisation model, five three-stages of roadmaps were selected. The objective was to select building roadmaps from different countries that were considered plausible after the analysis above. After screening all roadmaps, the IDs 18 (from Portugal), 18, 19 and 24 (from Poland) and 38 (from Bulgaria) were selected. Figure 16 (a-c) shows the primary energy demand and CO_2 emission development from each roadmap per country. The selected buildings are highlighted in dotted lines:



(a) Portugal



(b) Poland



(c) Bulgaria

Figure 16: Primary energy and CO_2 emission development for different roadmaps per country

Table 7 presents other building characteristics from the selected buildings, including building ID, country, year of construction, net floor area, and year of heating system replacement.

Table 7: Cases studied building data, Source: (Mellwig, Werle, and Lempik 2019)

ID	Country	Year of construction	Net floor area [m2]	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

Table 8 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. The table also illustrates the variety of solutions provided by the energy auditors. As the table shows, not all roadmaps foresee the heating system replacement (for example, building ID 2), which indicates that decarbonisation targets were not the focus of some roadmaps and fossil fuel heating supply is still suggested in the daily practice. Another relevant observation is that in step 2 for Building 1, negative final energy saving is observed. This is because, in general, biomass boilers are less efficient. However, the lower efficiency is compensated by, the lower carbon intensity. The data in Table 8 was prepared, serving as input data to the staged retrofitting optimisation model explained next.

Table 8: Step-by-step roadmaps and model input data per step: building 1–5, Source: (Mellwig, Werle, and Lempik 2019)

ID	Stage	Measure/Package of measures	Primary energy demand [kWh/m2]	Useful energy demand [kWh/m2]	Carbon emission [kg/m2a]	Investment cost [euro]	Main energy source
1	0	Status quo	600	327	100		electricity
	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	14.5	electricity
	2	Add a biomass boiler	51	112	7	3	wood
	3	Installation of individual inclined solar thermal system	27	87	4	2	wood
2	0	Status quo	474	427	86		natural gas
	1	Pipe insulation; Installation of a thermal solar system for domestic hot water	343	317	63	2.222	natural gas
	2	External Wall insulation;Roof insulation; Substitution of the old doors	163	154	30	17.384	natural gas
	3	Substitution of the old windows	134	127	25	9.16	natural gas
3	0	Status quo	382	344	70		natural gas
	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
	2	Roof insulation	153	140	28	5.21	natural gas
	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
	1	Substitution of the old doors	431	392	99	2.597	hard coal
	2	Insulation external walls	235	214	99	29.616	hard coal
	3	Insulation of ceiling	185	168	56	43.257	hard coal
5	0	Status quo	504	168	100		electricity
	1	External Wall insulation; Roof Insulation; Change glazing with energy saving glazing	300	100	13	9.537	electricity
	2	Installation of a thermal solar system for domestic hot water	227	92	12	2.55	electricity
	3	Substitution of the heating system by a heating pump	176	59	8	6.12	electricity

4.2.3 Workflow overview

The general approach consists of mainly four parts:

Part 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, the building material ageing process, and the interdependency of the measures;

Part 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;

Part III) Compare the results for different interdependency constraints in order to understand the effect of interdependency on the building's cumulated energy savings for the period up until 2050;

Part 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.

4.2.4 Model description

This chapter presents the framework to develop and apply an optimisation step-by-step retrofitting model, 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, and the building roadmaps applied are presented in section 5.2.2. The method relies on techno-economic specifications, as described below:

1) **Technical specifications:** specification of the renovation measures and their combination (stage), identification of building elements' material, specification of material's lifetime according to existing databases, and calculation of material's ageing process;
2) **Economic specifications**: investment costs per step, energy price development per energy carrier, and homeowner's budget restriction

Figure 17 presents the code architecture, especially specifying the input data requested.

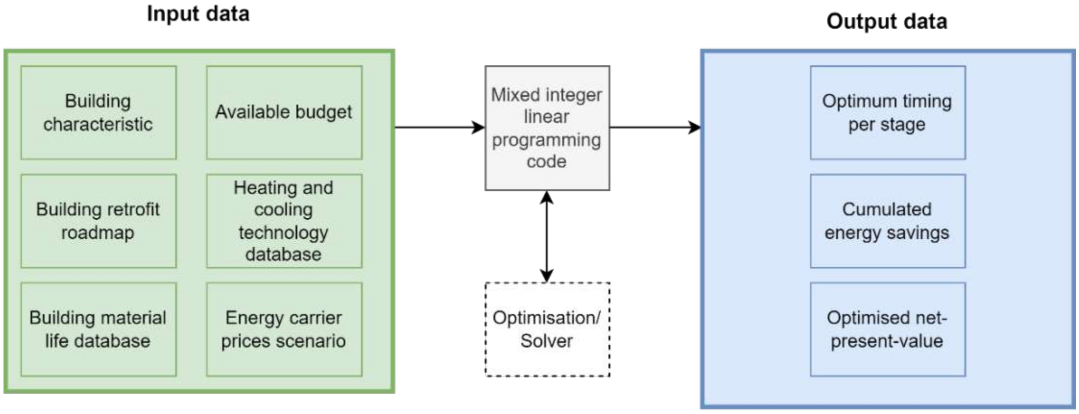


Figure 17: Code architecture staged retrofit optimisation model

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 (Hart 2017)and Gurobi solver(Gurobi 2020).

4.2.5 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) (Less and Walker 2014; Verbeeck and Hens 2005). 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 5.2.5.6. 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.

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

Equation 5

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

Equation 6 shows the objective function where for the maximised net present value (NPV), the optimum timing is calculated. The binary decision variables x, y and z representing each stage define if the stage is performed in the respective year or not.

$$\max \text{NPV} = f\{t, x, y, z\}$$

Equation 6

$s.t.$

$x \in \{0,1\}$

$y \in \{0,1\}$

$z \in \{0,1\}$

$x_t + y_t + z_t \leq 3$

$t \in T$

$\sum_t^T x \leq 1$

$\sum_t^T y \leq 1$

$\sum_t^T z \leq 1$

The model also 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 the full load operation of the replaced 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.

4.2.5.1 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 (ASS_t) minus the energy-related expenditures (IC, EC and OMC):

$$CF_t = ASS_t - IC_t - EC_t - OMC_t$$

Equation 7

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

4.2.5.2 Cumulated and allocated energy-related assets and budget restriction

The cumulated allocated asset (ASS_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 (ASS_{t-1}):

$$ASS_t = (INC_t * s) + ASS_{t-1}$$

Equation 8

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

These cumulated assets in year t (ASS_t) represent the available budget 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 available budget in year t (B_t) may be written as:

$$B_t = IC_t + EC_t + OMC_t$$

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

Equation 9

B; available budget [euro]; IC, the initial investment of retrofitting measures [euro]; EC, annual running energy costs [euro]; OMC, annual running operation and maintenance costs [euro]; f_l, loan or available incentive factor[%].

4.2.5.3 Investment costs

The initial investment (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:

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

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

Equation 10

IC, total initial investment [euro]; ICer, energy-related investment costs, for each retrofitting step (i) [euro]; ICman, maintenance investment cost, for each retrofitting step (i) [euro]; 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.

4.2.5.4 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 [90]:

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

Equation 11

EC, energy costs [euro]*; fed,* final energy demand [kWh]; *pr,* energy price [euro/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}:

$$\text{for, } x_t = 0,\ fed_{t+1} = fed_t$$

$$x_t = 1, fed_{t+1} = fed_t * f(IC_{er,i})$$

Equation 12

4.2.5.5 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}):

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

Equation 13

OMC, operation and maintenance costs [euro]; *IC*, initial investment of the active system [euro]; f; operation and maintenance factor [%].

4.2.5.6 Material's ageing process probability

The probability (p) of retrofitting measures (i) at the time (t) is defined by the Weibull distribution of the material's ageing process:

$$p_{t,i} = 1 - e^{-(\frac{t-t_{i,0}}{t_{i,L}-t_{i,0}})^m}$$

where, $t_0, m > 0$

Equation 14

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

4.2.5.7 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 ($t_{L,i}$), the depreciation time (t_P) and the optimum time delivered by the model (top):

for,

$$t < t_{L,i} : L_t = IC_i * \frac{t_{L,i} - (tp + top_i)}{t_{L,i} * (1 + r)^{tp}}$$

$$t \geq t_{L,i}: 0$$

Equation 15

L, residual value [euro]; IC total initial investment, for each step i [euro]; t_L, building materials and technical system lifetime for each step i [yr]; *tp,* depreciation time [yr]; top, optimum time defined by the optimisation model for each step i [yr].

4.2.5.8 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:

$$ES_i = \frac{fed_{sq} - fed_i}{fed_{sq}}$$

Equation 16

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

4.2.5.9 Cumulated energy savings

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

$$CES = \sum_{1}^{i} ES_i * p_i$$

Equation 17

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

4.2.6 Model assumption and input data

The model assumptions and input data used are explained below:

- **Renovation cycles**: the model delivers the optimum timing for one renovation cycle for the specified renovation period. This means that each step is performed one time. The model decides if the step should be performed (or not) and when (what year) – called the optimum timing (top).

- **Retrofitting measures and their investment costs (IC)**: in the staged approach, a step consists of one or more retrofitting measures (or a package of measures). This input data is defined in the building roadmaps.
- **Building material lifetime database (tL)**: a database of the building material and heating technology lifetime was set based on the literature review (Pfeiffer et al. 2010; BBSR 2017). 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[2]).
- **Material ageing rate (m)**: it was assumed as 6.5, based on the literature (Hansen 2010; Kockat 2011)
- **Heating and cooling system technology**: both currently installed and foreseeing in the roadmap are specified (per building). 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)**: energy prices and price development, as well as heating technology prices, were determined based on the literature review. Mainly, different modelling scenarios were used (Capros et al. 2018; Grave et al. 2016; European Commission 2019).
- **Optimisation period (T)**: an optimisation period of 30 years, from 2020 until 2050, was considered.
- **Depreciation time (tp)**: the depreciation time was considered 30 years.
- **Annually allocated energy-related asset (A)**: An annual allocated income of 3,000 euros 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 euros disposable income (INC). The disposable income assumption was based on a literature review of European's disposable income (Eurostat 2019; del Pero et al. 2016) 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 euros and a best-case scenario of 6,000 euros 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 is calculated with a conservative interest rate of 3%.
- **Number of stages (i)**: The model was outlined to provide the calculations for a roadmap with three stages (i = 3). 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 analyse the two different constraints, "dependency" or "no dependency," and the effects of whether or not stage 3 is performed.

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

4.3 Assessing staged retrofits in different case studies

To assess the different effects of the staged retrofits, the research question RQ3 is answered: "Which insights about staged retrofits and their impacts on optimised roadmap time, cumulative CO2 emissions and net present value are observed". Then, the mixed integer optimisation model developed and tested (as presented in chapters 5.2 and 6.2) is applied in two case studies:

(1) **Case study Spain**: The main focus of this case study is to better understand the effects of data-driven homeowner budget restrictions on the calculated optimised staged retrofitting time. Then, the results about data-driven budget restrictions (represented by the indicator "saving") in chapter 5.1 are directly used as input data into the mixed-integer optimisation model. The case study focuses on the data from 2015 Spain, also assessing different reference buildings of the Spanish building stock. This case study considers the following:
   - Different data-driven budget restrictions
   - Six Spanish building typologies were used as reference buildings

(2) **Case study Spain, Sweden and Germany**: The main focus of this case study is to compare reference buildings in Spain, Sweden and Germany with different measures of energy efficiency, the cost-optimal against the climate-optimal variant. This case study considers the following:
   - Cost-optimality methodology that uses the metric "global costs"
   - Cumulative CO_2 -emissions as a metric for climate optimality
   - Sensitivity analyses: interrupted roadmap and another roadmap variant (in addition to the sensitivity analysis presented and discussed in chapter 6.2.5)

For both case studies, a calculation module that automatically generates three-stage roadmaps was developed. Also, country-specific building typologies and other input data adaptations were added, as explained in the next chapter.

4.3.1 Adding new modules to the staged retrofit optimisation model

Figure 18 describes the overview of the method to assess staged retrofit optimum timing of different country-specific case studies and performing additional calculation and data preparation modules as described below:

- **Automatised three-stage roadmaps**: a new calculation module was added, where the roadmaps are automatically calculated (as described in chapter 5.3.2). Here, two possible combinations of measures per stage were considered, as introduced in chapter 4.4 and deeper analysed in chapter 5.3.2.
- **Country-specific initial investments**: the calculated roadmaps consider measure costs (installation, material and labour costs).
- **Data-driven budget restrictions**: the budget restrictions presented in Chapter 6.1 are used as input data, also taking into account the differences according to the household types classified by the dwelling type and ownership status.

- **Country-specific building typologies:** the building typologies for Spain were defined, taking into account the building characteristics per construction period, as discussed in Chapter 3.1.1.

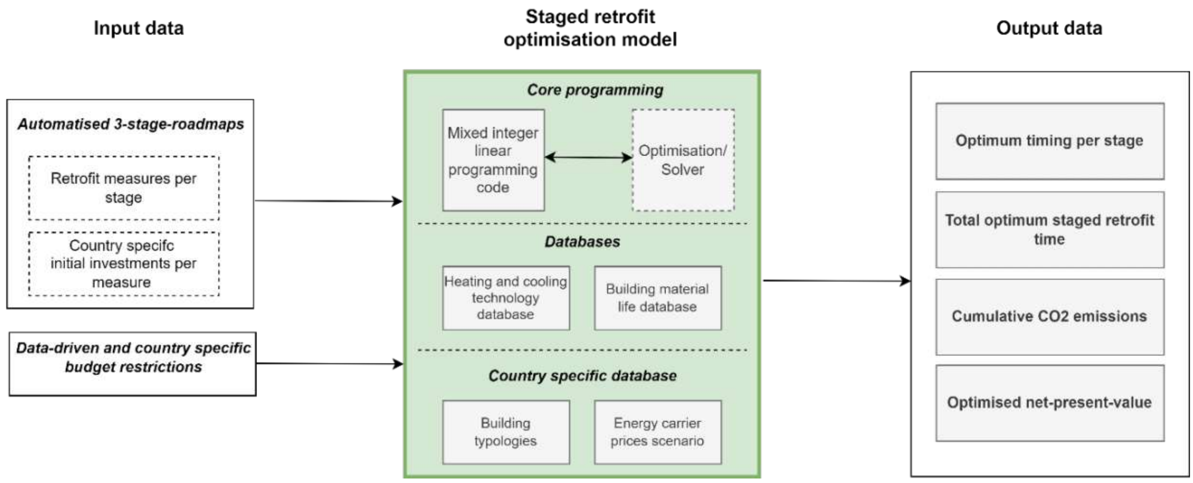


Figure 18: Overview of the method to assess staged retrofit optimum timing in a building stock level

4.3.2 Comparing cost and climate optimality of energy efficiency measures

The cost-optimal variant is assessed using the global costs (a commonly used method) under the assumption that all measures are performed at once. In addition to that, simplified and automatised three stages roadmaps are generated, also considering the different measures' energy efficiency standards. Next, a staged renovation mixer-integer optimisation model (MIPL) (I. Maia, Kranzl, and Müller 2021) is applied to minimise the roadmap time by calculating the optimum timing when each stage should be performed. The metric cumulative CO_2 emission is used to assess the climate-optimal variant under the consideration of time. Finally, the cost-optimal variant according to both metrics is compared. This approach is applied to reference buildings from three countries, Germany, Spain and Sweden, in other to cover different climatic conditions. The scope focuses mainly on the energy demand for space heating, which is the most affected by the considered renovation measures. In a country-specific analysis, space cooling (especially in Spain) could also be part of the scope. Figure 19 presents an overview of the workflow.

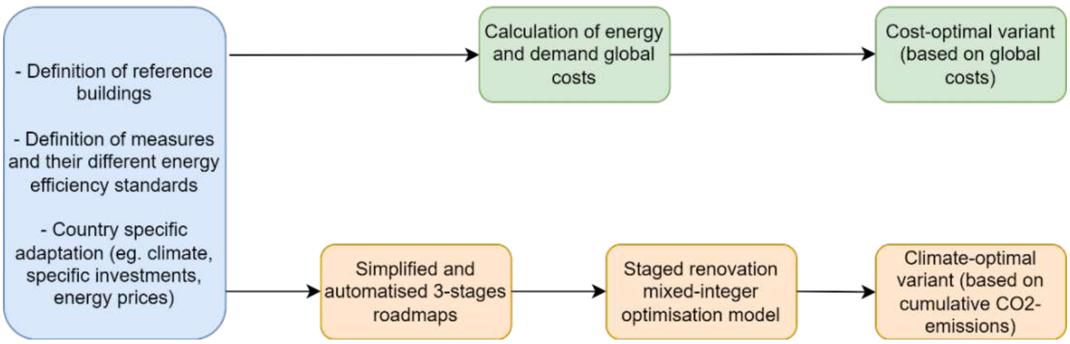


Figure 19: Method overview to assess cost-optimality using the indicator "global costs" and climate-optimality using "cumulative CO_2-emissions"

4.3.2.1 Cost-optimality methodology

According to the investment theory, different solutions lead to reduced costs in the future – also called cost-effective solutions. However, with the cost-optimal approach, the main goal is to find one solution for which the economic benefit is maximised. This means that the cost-optimal solution represents the lowest total running costs and initial investments over the building period (Stocker and Koch 2017). The calculation methods behind this methodology are mainly both a) building energy performance and b) economic analysis of investments (Mauro et al. 2015). In the cost-optimal methodology, the "global costs" are determined by initial investments, operational, maintenance and operation costs and disposal costs. 2010 the EPBD introduced the metric "global costs" (EU-Commission 2013) to calculate the minimum performance standards. The analysis performed by the Spanish Ministry is an example of this approach (Spanish Ministry of Public Works 2018).

The global costs are calculated according to (Ascione et al. 2017) according (EU-Commission 2013):

$$C_g(\tau) = C_I + \sum_j [\sum_{i=1}^{\tau} (C_{a,i}\,(j) * R_d(i)) - V_{f,\tau}(j)] \qquad \text{Equation 18}$$

C_g, global costs over the calculation period [euro]; τ, calculation period [yr]; C_I, initial investments of all measures [euro]; $Ca_{,i}$, operational costs during the year I for the measures j [euro]; j, energy efficiency measures; R_d if the discount factor for a year i [euro]; $V_{f,\tau}$ residual value of measures j at the end of the calculation period [euro]. It was considered a discount rate of 3%.

4.3.2.2 Climate-optimality

The climate optimality was measured using the metrics of cumulative CO_2 emissions, explained in Equation 22.

$$cumCO2 = \sum_1^i CO2_i * p_i \qquad \text{Equation 19}$$

cumCO2, cumulative CO_2 emission [$kgCO_2$]; CO2, CO_2 emission after performing the measures foreseen in stage i [kgCO2/ yr]; p, the period of the performed stage (until the next stage is carried out) [yr]; i, number of stages of the renovation roadmap. For single-step renovation, i = 1. In the present analysis model, i = 3.

4.3.3 Developing automatised roadmaps

In real life, this roadmap can also be an individual building renovation roadmap developed by an energy assessor together with the building owner for a certain building (as presented in chapter 5.2.2). For modelling purposes and upscale to the building stock level, this process should be automatised. The deterministic definition of roadmaps (Chapter 4) showed two options for three-stage roadmaps, where the main difference is the stage containing the measure cellar ceiling insulation. In option 1, this measure is combined with the heating system replacement in stage 3, while in option two, it is combined with the measures of external wall insulation and window replacement in stage 2. Figure 20 shows the possible combinations of measures per stage. The sequencing of the stages is indirectly defined by the optimisation model when calculating the optimum timing when each stage should be performed. The distribution of measures per stage represents a dilemma. On the one hand, by performing more measures in a stage, it may accelerate the achievement of energy savings. On the other hand, it can generate an economic burden for homeowners, consequently postponing the implementation of the measure. Then, the optimum timing of the stages in both these roadmap options is compared.

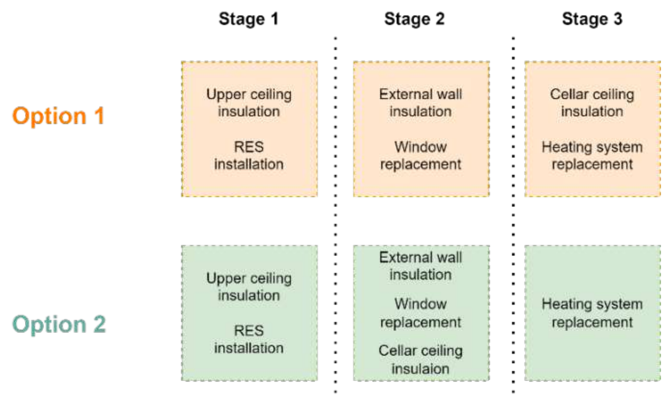


Figure 20: Two options of how to combine different measures in an automatised three-stage retrofit roadmap

Besides the allocation of measures per stage described above, the automatised generation of roadmaps includes calculating based on a target energy standard previously defined: the building energy performance development over the staged retrofitting and the initial investments of each stage. Figure 21 shows the workflow that was implemented as programming code in Python. The workflow consists of input data and database information (in “grey”), such as building geometry and construction period and renovation costs database. The measures and roadmap options (in “yellow”) are according to Figure 20. The calculation modules (in “blue”) are the investment costs calculation, the new building parameter and the energy demand development. The building energy demand calculation is a monthly-base steady-state calculation according to the German norm DIN 18999 that relies on the ISO 52000 series (Baunormlexikon 2018). The investment costs were estimated per measure (and a package of measures) based on a literature review (Hummel et al. 2021). The automatised roadmap includes needed initial investments per stage and energy demand development and is the main output (in “lila”). This workflow was carried out for different Spanish building typologies defined in the next chapter.

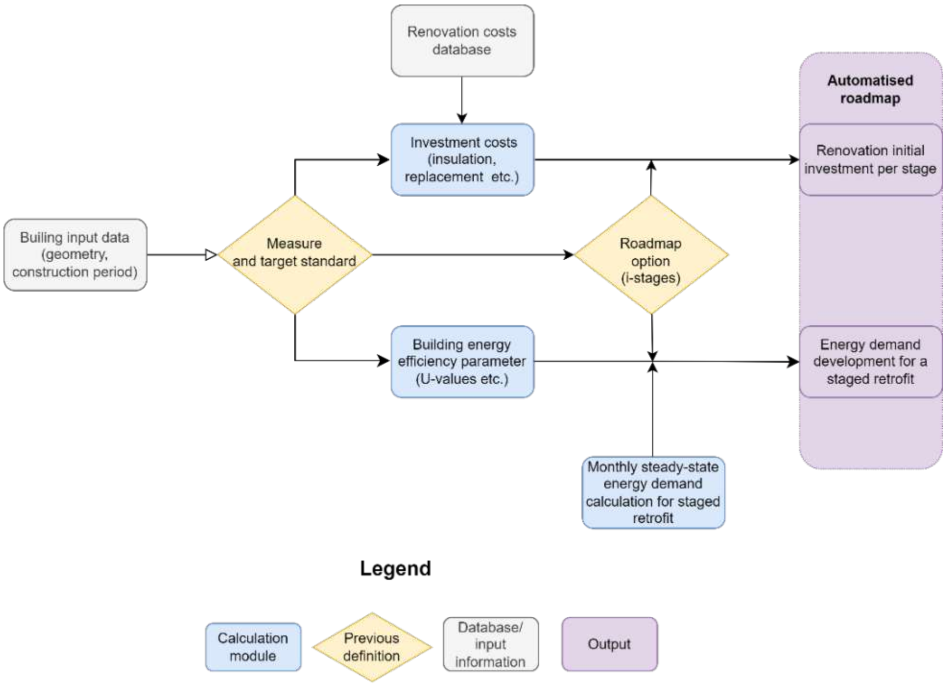


Figure 21: Workflow for generating an automatised building roadmap

4.3.4 Spanish building typologies

Table 9 shows the input parameter per building typology for single-family houses in Spain (Continental). The Spanish building stock is represented by six building construction periods. The typology-specific envelope quality, space heating and DHW systems are presented.

Table 9: Technological and geometry characteristics of the reference buildings for Spain. Source: (EPISCOPE project 2016)

Parameters\ Countries		**Spain (Continental)**					
	Construction year	until 1900	1901-1936	1937-1959	1960-1979	1980-2006	after 2007
	Ref.floor area [m2]	55	202	780	171	163	119
Envelope							
Roof 1	Type	Pitched roof wooden frame	Ventilated flat roof with metal frame	Ventilated flat roof with with concrete horizontal framework	Ventilated pitched roof wooden frame and suspended ceiling	flat roof: one-way framework with prestressed joint	flat roof: one-way framework with prestressed joint
	Surface area [m2]	50	86.5	166.4	63.8	132	67.7
	U-value [W/(m2K)]	02.08	03.08	2.73615	4.17	0.61	0.48
Wall 1	Type	masonry of natural stones	masonry of coating bricks	masonry of coating bricks	cavity wall: brick,air cavity	cavity wall with insulation inside the cavity	cavity wall
	Surface area [m2]	65.8	258.2	463.9	312	234.1	176.4
	U-value [W/(m2K)]	0.24	2.94	2.56	1.33	0.6	0.48
Floor 1	Type	one-way framework, wooden joints	flooring on the ground	one-way framework, metal joints	flooring on the ground	flooring on the ground	one-way framework with prestressed joint
	Surface area [m2]	50	86.5	145.8	90	107.2	67.7
	U-value [W/(m2K)]	2.38	0.85	1.83	0.85	0.85	1.31
Window 1	Type	wood frame, single glazed	metal frame, single glazed, no	metal frame, single glazed, no thermal break	metal frame, single glazed, no thermal break	PVC frame, double glazed	one-way framework with prestressed joint
	Surface area [m2]	4.4	28.5	43.5	12.6	65.9	19.9
	U-value [W/(m2K)]	5	4.59	4.59	4.59	3.09	3.09

4.3.5 Reference buildings for country comparison

To define the reference buildings, both techno and economic characteristics are considered. For the techno-characteristics, the oldest construction period per country was chosen for the building type single-family houses. Herefore, the TABULA database (EPISCOPE project 2016) served as a basis for the country-specific typology. Table 10 presents the technological and geometry characteristics of the reference buildings.

Table 10: Technological and geometry characteristics of the reference buildings for Spain, Germany and Sweden. Source: (EPISCOPE project 2016)

Parameters\ Countries		**Germany**	**Spain**	**Sweden**
	Construction year	**1949-1957**	**1901-1936**	**until 1960**
	Ref.floor area [m2]	111	202	106
Envelope				
Roof	*Type*	tilted roof with clay/straw filling between rafters	Pitched roof wooden frame	horizontal wind
	Surface area [m2]	125.4	86.5	125
	U-value [W/(m2K)]	1.4	3.08	0.29
Wall	*Type*	brickwork	masonry of natural stones	light concrete block
	Surface area [m2]	117.8	258.2	100
	U-value [W/(m2K)]	1.4	2.94	0.6
Floor	*Type*	wooden beam ceiling	one-way framework, wooden joints	concrete slab
	Surface area [m2]	79.9	86.5	125
	U-value [W/(m2K)]	0.82	0.85	0.28
Window	*Type*	wooden window with dual-pane glazing	wood frame, single glazed	window
	Surface area [m2]	18.4	28.5	22
	U-value [W/(m2K)]	2.8	4.59	2.34
Space heating				
Heat generator	*Type*	low temperature non-condensing boiler / from 1987 to 1994	gas old boiler (non-condensing)	heating system with fuel, oil
	energy carrier	natural gas	natural gas	heating oil
	energy expenditure coefficient	1.29	1.15	1.15
	fraction of heat production	100%	100%	100%

4.3.6 Energy efficiency standard measures

Besides the techno-characteristics, the staged renovation MILP requests as input the parameter budget restriction of the household (as explained below). For all countries, an annual budget restriction of 3,000 euros was considered. Then, the renovation measures were defined as presented in Table 3, and their energy efficiency standards were represented by the insulation ranges, windows U-values and efficiency of the heating system. As a heating system measure, the replacement of the existing fossil system by an air-to-air heat pump with COP equal to 3.0. The choice of a heat pump as a heating system replacement option has as the main reason for the fact that many EU countries are incentivizing the roll-out of heat pumps as a preferable renewable, decentralized heating system. Other renewable heating system options would be, for example, biomass or district heating, which depends more on local conditions – then more appropriate for specific solutions but not for generalised analysis. The combination of these measures and their different energy efficiency standards generates 16 possible combinations.

Table 11: Considered measures and their energy efficiency standards

ID	Insulation thickness [cm] - External wall	Insulation thickness [cm] - Floor	Insulation thickness [cm] - Roof	U-value [W/(m² K)] - External wall	U-value [W/(m² K)] - Floor	U-value [W/(m² K)] - Roof	U-value [W/(m² K)] - Window	Heating system
1	15	15	20	0.21	0.18	0.14	0.70	Air source heat pump
2	15	15	20	0.21	0.18	0.14	0.95	Air source heat pump
3	15	15	25	0.21	0.18	0.12	0.70	Air source heat pump
4	15	15	25	0.21	0.18	0.12	0.95	Air source heat pump
5	15	20	20	0.21	0.15	0.14	0.70	Air source heat pump
6	15	20	20	0.21	0.15	0.14	0.95	Air source heat pump
7	15	20	25	0.21	0.15	0.12	0.70	Air source heat pump
8	15	20	25	0.21	0.15	0.12	0.95	Air source heat pump
9	20	15	20	0.16	0.18	0.14	0.70	Air source heat pump
10	20	15	20	0.16	0.18	0.14	0.95	Air source heat pump
11	20	15	25	0.16	0.18	0.12	0.70	Air source heat pump
12	20	15	25	0.16	0.18	0.12	0.95	Air source heat pump
13	20	20	20	0.16	0.15	0.14	0.70	Air source heat pump
14	20	20	20	0.16	0.15	0.14	0.95	Air source heat pump
15	20	20	25	0.16	0.15	0.12	0.70	Air source heat pump
16	20	20	25	0.16	0.15	0.12	0.95	Air source heat pump

5 Results and discussion

5.1 Insights about natural gas expenditure, income and savings

The results section has four parts: 1) the selection of datasets based on the data preparation and comparison steps, 2) the modelling approach, including the description of the regression model's characteristics; 3) a statistical description of the annual natural gas expenditures, incomes and savings for the different household types; and 4) a more detailed statistical description of the variables income, natural gas expenditure and saving for the households with high natural gas expenditures.

5.1.1 Selected dataset after dataset comparison

Primarily, the EU-SILC and HBS datasets were studied separately in the data preparation (Figure 12) to select the country to which the modelling would be applied. Initially, nine countries of interest were pre-selected due to their different climate zones and population sizes: Austria, Bulgaria, France, Germany, Italy, Netherlands, Romania, Spain, Poland, Portugal and Sweden. However, Austria and Portugal had to be eliminated at the beginning as not all HBS 2015 variables are available for these countries.

The combination of available and complete data indicates if the data was appropriate to be used. All countries showed a high percentage of complete data for a matching or interest variable. Data from Germany was excluded because the variable of interest was not available in the EU-SILC dataset. France, Italy and the Netherlands were also excluded because either the HBS or the EU-SILC were deemed not appropriate. The remaining countries were Bulgaria, Romania, Poland, Sweden and Spain, for which the presented methodology could be conducted. Then, finally, the variable-by-variable comparison led to the selection of Spain data. Figure 22 shows the comparison of two variables, "Economic status" (a) and "Degree of urbanisation" (b), respectively. The variable "Economic status" was discarded from the modelling because of the high difference between both datasets (especially in the category "working").

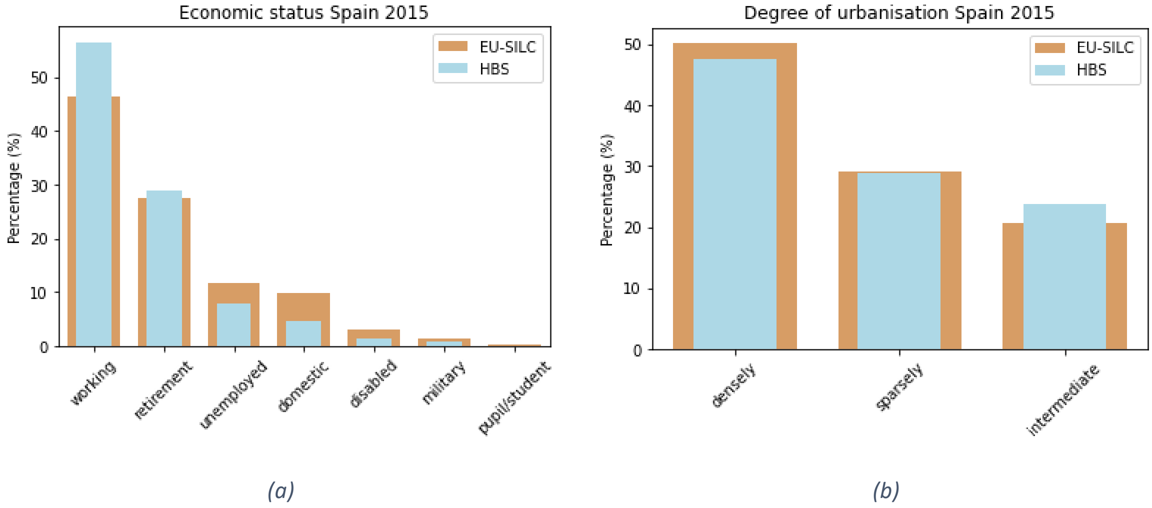


Figure 22: Comparison between the variable distribution between the datasets EU-SILC and HBS, (a) variable "Economic status" and (b) variable "Degree of urbanisation".

5.1.2 Statistical matching Imputing "dwelling type" into HBS

The sample was split in 80/20 (training and testing, respectively) after also testing the data split 70/30. The coefficient related to the variable "disposable income" was low, which leads to the conclusion that this variable is not very relevant to the model. The estimated coefficients show the highest relationship between single-family-house and degree of urbanisation "sparsely" and "intermediate", meaning that people that live in sparsely or intermediate populated areas have higher chances of living in single-family houses. The variable status employment "employer" also has a positive relation with the variable of interest. This means that employers have higher chances to live in single-family houses. The marital status variable categories "never married" and "separated or widowed" have a negative relation with the interest variable. The same applied to the variable ownership status "rented". This means that these groups of people have a higher chance of not living in single-family houses, living mainly in apartments. Table 12 presents the logistic regression coefficients where 11335 on 11371 degrees of freedom were observed.

Table 12: Logistic regression coefficients

Coefficient Name	Coefficient Estimation	Coefficient Standard Error	Coefficient Z-score	Probability (>|z|) ***
(Intercept)	-1,820	45	-40,346	< 2E-16
marital_status_never_married	-288	65	-4,440	9.01E-06
marital_status_sep.widowed	-226	61	-3,683	231
status_employment_employer	447	58	7,713	1.23E-14
ownership_status_rented	-505	65	-7,802	6.12E-15
degree_urbanisation_intermediate	1,393	59	23,741	< 2E-16
degree_urbanisation_sparsely	2,743	56	49,381	< 2E-16
(***Signif. codes: 0 '***')				

The ROC Curve (Figure 23) shows the model's sensitivity (true positive rate) of 0.774 and the specificity of 0.718, which together define the ability of the model to predict the probability of the interest variable and the threshold and define the cut-off point for the binary value. In this logistic regression model, the cut-off point of 0.320 defines the probability for which higher values are predicted as single-family houses (1) and lower values as apartments (0). The confusion matrix (Figure 24) compares the predicted values with the real values in grey for SFH and red for MFH. In the test base, 1,258 observations were predicted as apartments (0) and were apartments in the sample; 490 were predicted as single-family houses and were single-family houses (1). Then, 289 observations were predicted as single-family houses but were apartments, and 239 were predicted as apartments but were single-family houses. In general, the model presented an accuracy of 77% which is considered a good prediction capability.

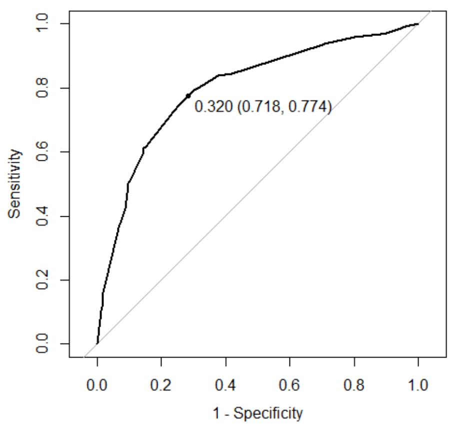


Figure 23: ROC curve

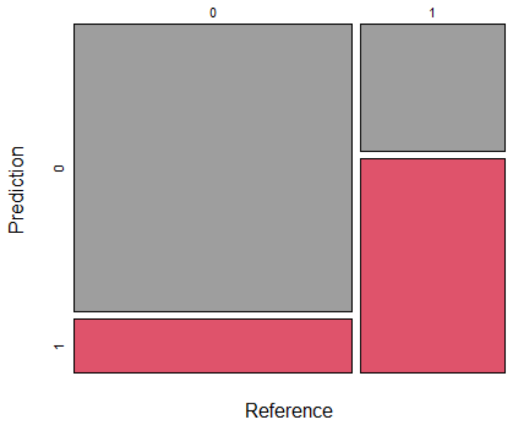


Figure 24: Confusion matrix

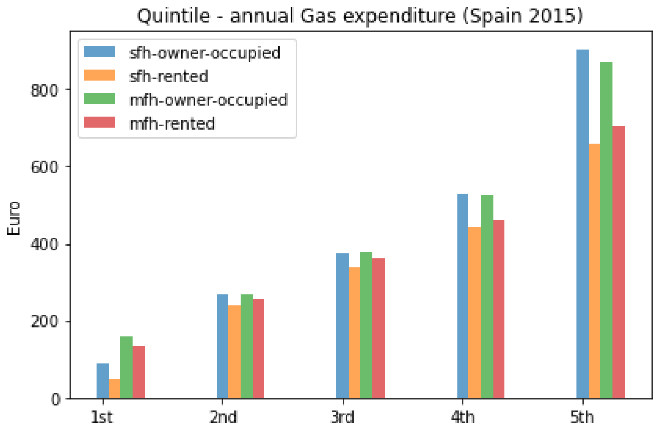
To predict the interest variable “dwelling type”, the model in Table 12 was adjusted with the inclusion of a residual with zero means and 1.7 standard deviations according to Stage II in Figure 14. The validation of the results consisted of comparing the shares of types in the donor SILC data with shares in the synthetic HBS data. Table 13 shows an acceptable range difference between 2.9% and -3.5%. In general, in the analysed 2015 data from Spain, the MFH owner-occupied have a higher share of observations, followed by SFH owner-occupied, MFH rented, and SFH rented.

Table 13: Model validation: comparison of household type share between generated synthetic data and donor dataset

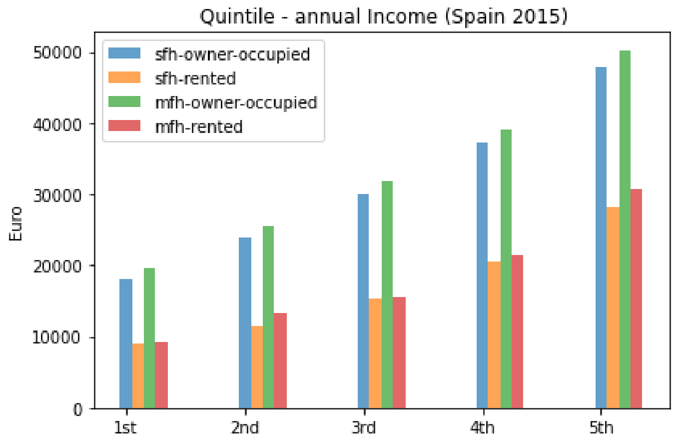
Household type	Synthetic HBS data [%]	Donor SILC [%]	Difference [%]
MFH-owner-occupied	55	52	3
MFH-rented	10	13	3
SFH-owner-occupied	32	30	2
SFH-rented	3	5	2

5.1.3 All households: annual natural gas expenditure, incomes and savings

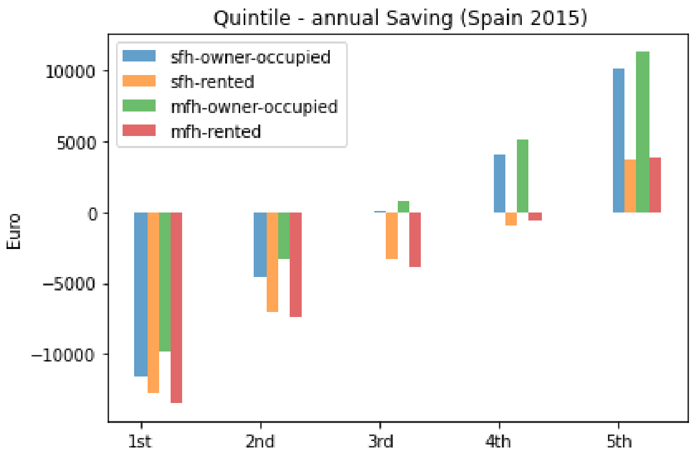
Figure 25 shows the quintiles distribution for the 2015 Spain data represented by the three variables annual natural gas expenditures, income and household savings. Four household types are represented: SFH owner-occupied, SFH rented, MFH owner-occupied, and MFH rented.



(a)



(b)



(c)

Figure 25: Quintiles distribution for 2015 Spain data. The three variables a) natural gas expenditure, b) income and c) savings are represented.

Figure 25a shows that across all quintiles owner-occupied (SFH and MFH) households have higher natural gas expenditures than rented ones, being a maximum expenditure of 905 euros (SFH owner-occupied) and a minimum of 75 euros (SFH owner-rented). Also, the SFH owner-occupied households have the highest natural gas expenditure quintiles, except in the first quintile, where MFH-owner-occupied is higher. The same figure also shows that the difference between the minimum and maximum natural gas expenditure of the four different household types is higher in the first and fifth quintiles, showing a higher heterogeneity in these parts of the sample.

Figure 25b shows a general pattern that owner-occupied households have higher incomes than rented, and the difference between single and multi-family houses does not play a relevant role in this variable. In the first quintile, the difference between MFH rented versus owner-occupied is about 47%, while in SFH, this difference is 50%. In the fifth quintile, the difference between MFH rented versus owner-occupied is about 61%, while in SFH, this difference is 58%. In general, it can be said that the difference between rented and owner-occupied annual income increases according to the sample part.

Figure 25c shows that most rented households have negative savings (about 80%, which means first to fourth quintiles), with only 20% positive savings (fifth quintile). For owner-occupied households, the negative savings percentage decreases to 40% of the observations, and the positive savings to 60%. In general, it means that owner-occupied households can save more than rented ones. Negative savings means that the households declared higher total expenditures than their income in the survey's year. In the third and fourth quintiles, owner-occupied households have positive savings, while rented have negative savings.

5.1.4 High natural gas expenditure households

The HBS dataset divides energy expenditure according to four energy carrier categories: electricity, natural gas, solid (coal) and liquid. In general, the natural gas consumption in a household can be for the following building services: cooking, space heating and domestic hot water heating. However, the energy bills are normally for electricity and natural gas separately, but not specifically for the building service. A clear separation of the expenditure per building service is not possible with the current information in the dataset. 56% of the households use natural gas as the main energy carrier.

The expenditure thresholds were defined according to the quintiles presented in Figure 25 and represent high, middle and low annual expenditures:

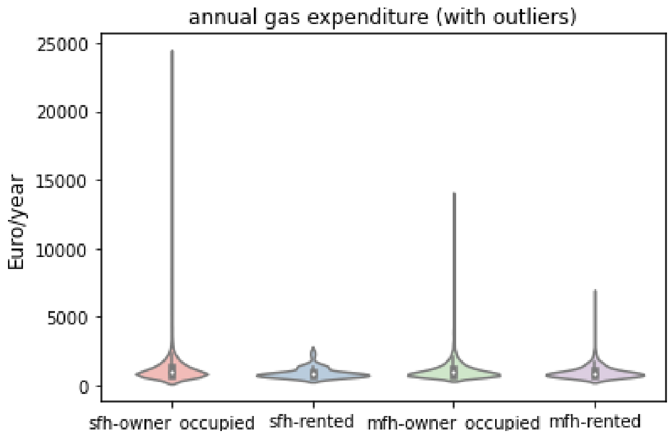
- High expenditure: higher than 600 euros/year
- Middle expenditure: between 350 and 600 euros/year
- Low expenditure: lower than 350 euros/year

Table 14 shows the number of observations and total share per household type and natural gas expenditure range: 28% have high expenditure, 26% have middle expenditure, and 46% have low expenditure. Furthermore, in the group of high expenditure, the share of owner-occupied households is higher than 90%.

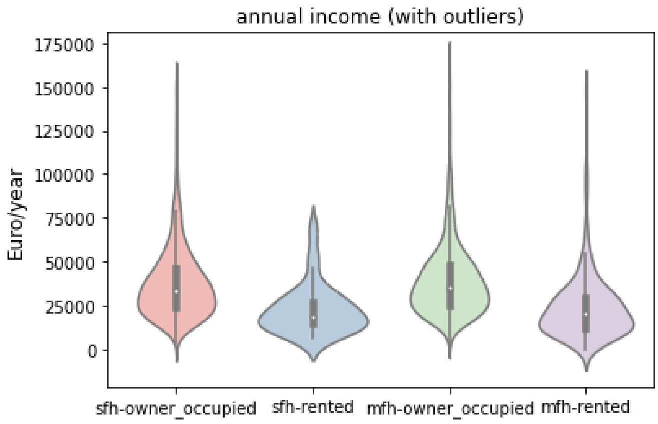
Table 14: Number of observations per natural gas expenditure (euro/year) and household type (in %)

Type	>=600 euro/year	>=350 and <600 euro/year	<350 euro/year
SFH-owner-occupied	1024	847	1536
SFH-rented	52	75	139
MFH-owner-occupied	2059	1833	3219
MFH-rented	249	326	555
Total share	28%	26%	46%

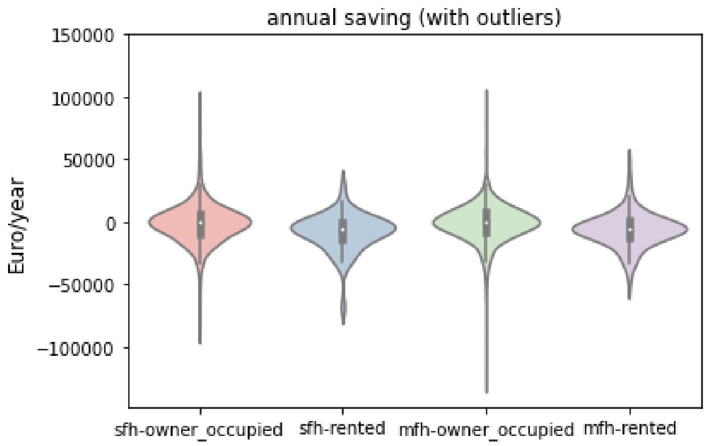
For the households with high natural gas expenditure (above 600 euros annually), the three variables natural gas expenditure (a), income (b) and saving (c) are described in Figure 26. The main intention is to understand if this group would be "able to pay" for financing energy efficiency measures (for example, retrofitting) to reduce their energy expenditures.



(a)



(b)



(c)

Figure 26: The households with natural expenditures higher than 600 euros annually were selected. The variables a) natural gas expenditure, b) income, and c) savings are used to show the distribution.

Figure 26a shows the annual gas expenditure of all observations. Outliers are observed in owner-occupied households (SFH and MFH), especially in SFH owner-occupied with a maximum of 25.000 euros. However, the means by household type are not that significantly different, with about 10% between the highest and the lowest mean: 1.112 euros (SFH owner-occupied), 1.188 euros (MFH owner-occupied), 1.015 euros (MFH rented) and 953 euros (SFH rented).

Figure 26b shows the annual income. The annual income mean differs by about 70% between the highest and the lowest mean. According to the types, these means are 39.223 euros (MFH owner-occupied), 30.000 euros (SFH owner-occupied), 23.756 euros (MFH rented) and 22.926 euros (SFH rented). The MFH owner occupied the type with the highest number and highest value of outliers (until about 175.000 euros).

Figure 26c shows the annual savings. There are negative saving means in all household types. Also, the difference between owner-occupied and rented households is observed: the ranges for rented households (both positive and negative) are shorter than for owner-occupied. This indicates a higher heterogeneity of savings in owner-occupied households. The annual saving means according to the household types is: - 522 euros (MFH owner-occupied), - 1.104 euros (SFH owner-occupied), - 6.181 euros (MFH-rented) and - 7.892euros (SFH-rented).

5.1.5 Discussion

The results were validated using existing literature. The mean of annual saving was negative for all types, which is a strong indicator of household budget restrictions, as also concluded by the authors F. Oehler et al. (Oehler, Rioboo, and Pallaro 2021). Households with negative savings or debts have even lower chances of investing in retrofitting without any attractive incentive available or financing schemes. There are different reasons for the negative saving: household expenditures might indeed be higher than income, or income sources may not have been declared. To prove these reasons, additional information about financial loans and debts would support the interpretation of the results that need to be considered; however, this information was not available in the data sources. Also consistent with the calculated negative saving mean, national statistics “Household net saving rate[3] Spain 2001-2020” show an estimated 2% saving rate in the period between 2012 and 2018, possibly reflecting post-2008 crisis effects compared to an 11% rate in 2005 (Statista 2022). The net household savings as a share of a household’s net disposable income shows the ability of the average household to save money. More specifically, it shows what portion of household incomes were saved. Then, a 2% saving rate shows, on the hand, a low capacity of households to save money. On the other hand, as a macroeconomic indicator, it indirectly shows that a portion of households may have negative savings, as presented in the results. Compared to 2015, the economic conjuncture of the last years since 2020 has significantly changed due to the COVID-19 pandemic, higher inflation, and soaring natural gas prices, which all worsened households’ budget restrictions. The main findings go beyond the quantified results: the building stock is not as dynamic or as responsive as other sectors, especially because of the ownership structure. This is a very important aspect that influences deep renovation activities.

[3]The net household savings as a share of their net disposable income shows the ability of the average household to save money. More specifically, the income portion that was saved.

Finally, the higher natural gas expenditures in single-family houses are an indication of higher space heating expenditures due to thermal losses through the building envelope compared to multi-family houses. An analysis relating the natural gas expenditure to the heating service requires information about the climate region (at least at a NUT3 or LAU level) and the building energy class, especially in a country like Spain with significant climate differences. These are considered follow-up analyses that involve extending the generated synthetic dataset with new variables. Another alternative is performing the statistical matching with other data sources, for example, the energy performance certificates (EPCs) that are considered an important source of building-specific data.

Other follow-up activities to extend the generated synthetic dataset:

- Add socio-economic variables as additional household characteristics, i.e., urbanisation degree, family composition, or the inhabitants' age. These characteristics may influence energy consumption and impact the decision to retrofit, also supported by (Cai and Jiang 2008).
- Add the variable "ability to keep the household warm" (available in the EU-SILC) to express household comfort levels and relate them to energy expenditure.

5.2 Optimum timing and sensitivity analysis

The sequence from the iBRoad roadmaps was compared with the optimisation model to validate the model. Chapter 5.2.2 presents the optimum timing and compares the results of two different constraint variants that represent the interdependency of the steps. Chapter 5.2.3 provides a comparison between both single-step and step-by-step approaches. Chapter 5.2.4 presents the results of the net present value.

5.2.1 Comparison with real-life roadmaps

Figure 27 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 "no 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.

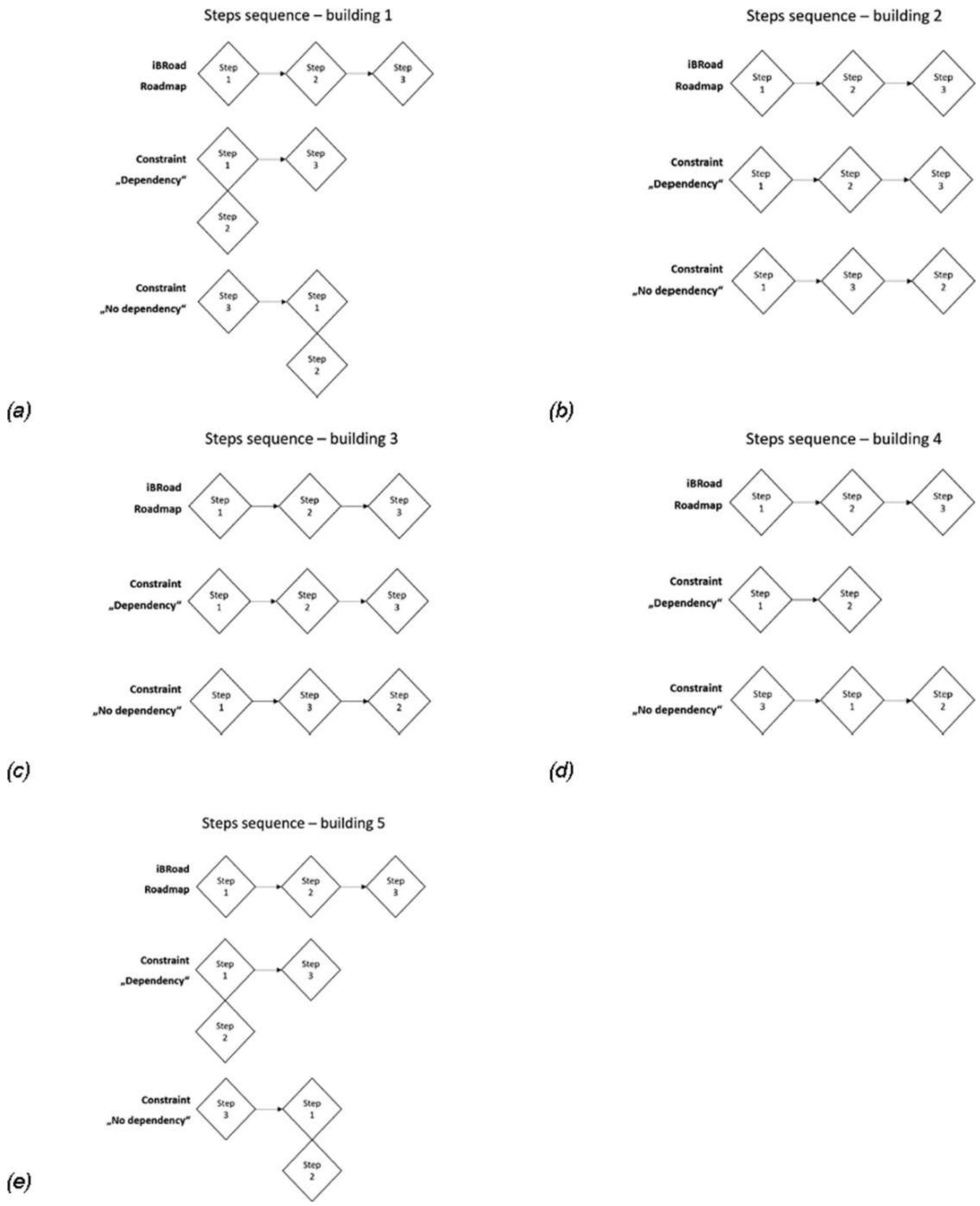


Figure 27: Steps sequence - building 1 to 5. The steps sequence is defined in the iBRoad roadmaps and in the optimisation model using both constraint variants "dependency" and "no dependency."

5.2.2 Comparison between different constraints

Table 15 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."

Table 15: Optimum calculated year when each step should be performed – two constraint variants that represent the interdependency of the steps "dependency" and "no dependency."

ID	Renovation step	Dependency between steps	No dependency 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

"Dependency" suggests dependency on the sequence 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 Steps 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 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 accumulate 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. Figure 28 below shows a comparison of the cumulated energy savings (for the period between 2020 and 2050) for all five test cases and for each constraint variant “dependency” and “no dependency”. The cumulated energy savings corresponds to the area below the graph lines (blue and red, respectively).

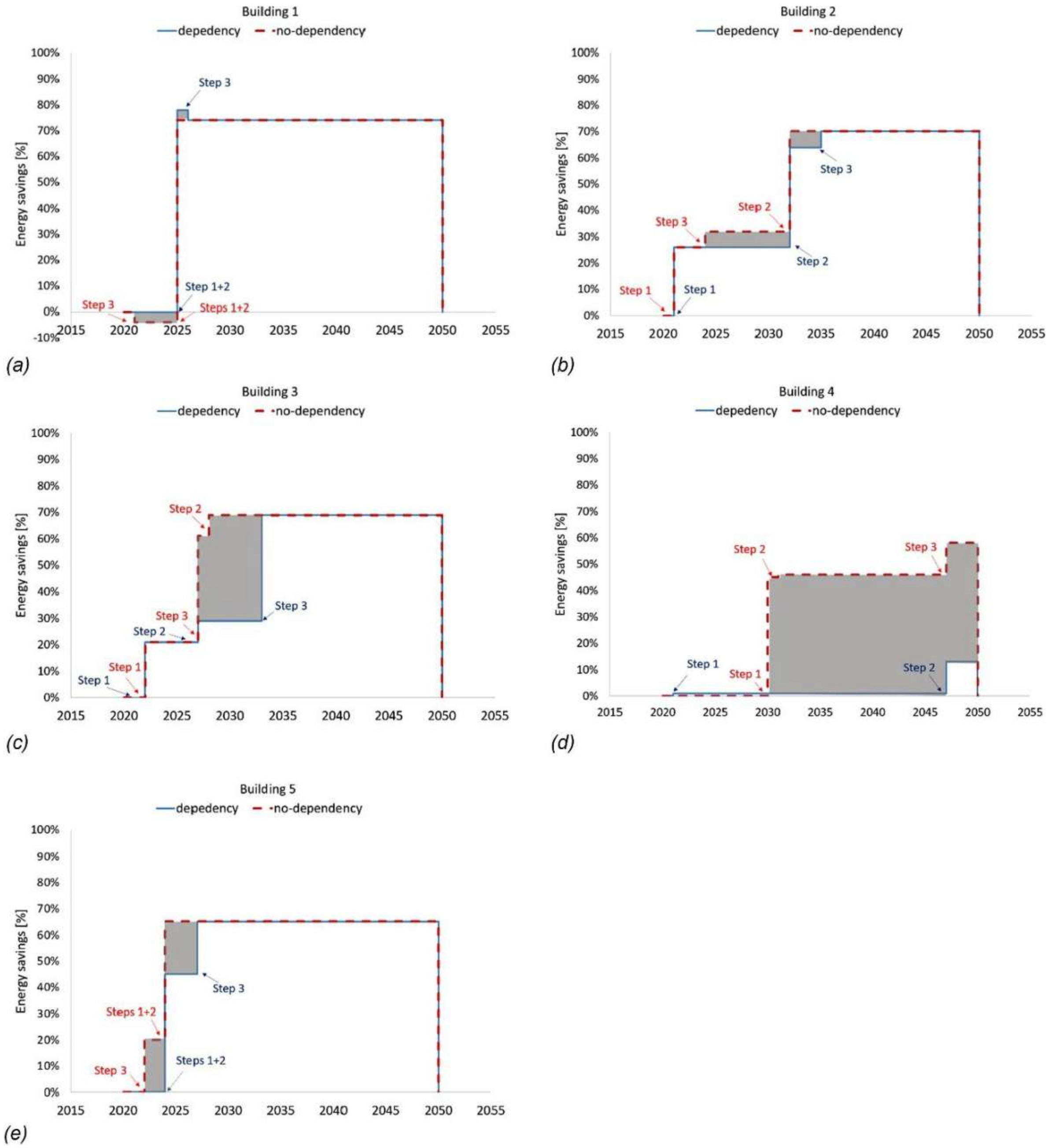


Figure 28: Cumulated energy savings comparison – buildings 1 to 5. The graphs show a comparison between both constraint variants: “dependency” (blue line) and “no dependency” (red line). The arrows show which step is performed. The grey areas indicate the difference in the cumulated energy savings between both variants.

The grey area indicates the difference between the cumulated energy savings between both variants. The arrows indicate which step is being performed:

- *Building 1*: The negative final energy demand savings happen 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 with “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 with “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 with “dependency”, it would be for 7 years. In general, it was observed that the constraint “dependency” enables the heating system to operate for a shorter time than 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.

5.2.3 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 Figure 29 below. 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 15) by annually allocating the energy-related asset (A) (chapter 5.2.5.2).

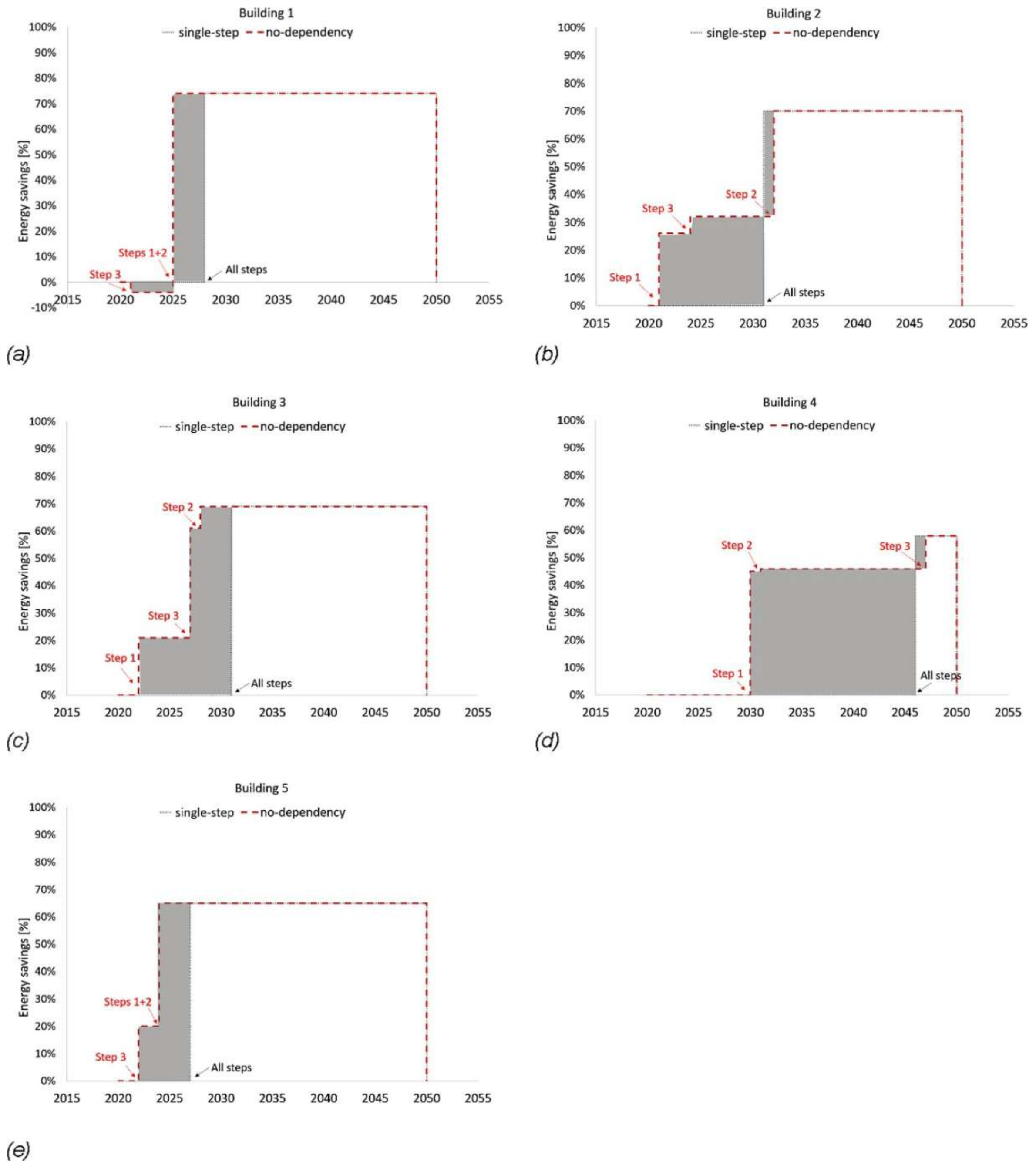


Figure 29: Cumulated energy savings comparison – buildings 1 to 5. The graphs show a comparison between both: step-by-step – variant "no dependency" (red line) and single-step (black line). The arrows show which step is performed. The grey areas indicate the difference between the cumulated energy savings between both variants.

Figure 29 above shows the cumulated energy savings per renovation approach (single-step and step-by-step) for each of the five buildings. The grey areas show the cumulated energy savings difference. In all five cases, the step-by-step approach presents 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 16.

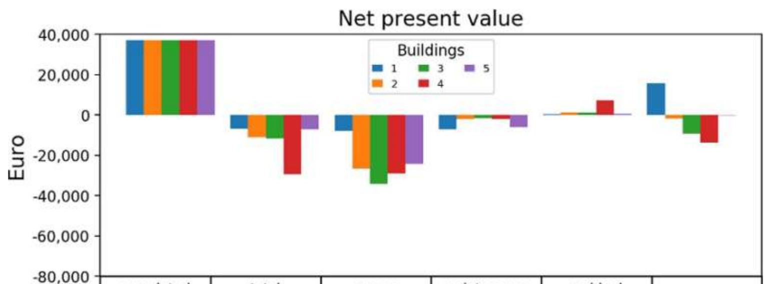
Table 16: Cumulated energy savings per renovation approach (single-step and step-by-step) - building 1 to 5.

ID	Cumulated energy savings [%yr] 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

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 step-by-step retrofitting, on the other hand, the energy savings increase gradually and are performed according to the 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.

5.2.4 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 in Chapter 5.2.5. 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. Figure 30 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.



	cumulated asset	total investment	energy expediture	maintenance expenditure	residual value	net
ID 1	37079	-6820	-7989	-7088	394	15576
ID 2	37079	-11087	-26780	-2245	1123	-1909
ID 3	37079	-11768	-34120	-1566	1034	-9341
ID 4	37079	-29519	-29268	-2065	7094	-13679
ID 5	37079	-7233	-24256	-6179	436	-153

Figure 30: Net present value of building's cash flow - building 1 to 5.

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 6.2.5 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 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.

5.2.5 Sensitivity analysis

This chapter investigates the sensitivity of the model when varying the parameters of budget restriction (section 6.2.5.1), energy prices (section 6.2.5.2) and renovation costs (section 6.2.5.3).

5.2.5.1 Budget restrictions

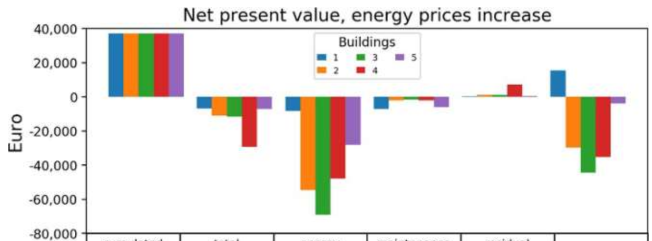
Table 17 presents the optimum year for three different annual budgets (900, 3,000, and 6,000 euros). It presents a sensitivity analysis of how the calculated optimum timing may change based on the homeowner's budget restriction. This table answers RQ3, as it shows that a lower budget may delay the optimum 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. Equation 12 defines 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 an available budget) might represent a higher total energy-related investment. Furthermore, a high budget restriction does not necessarily result in earlier optimum timing.

Table 17: Comparison of the optimum year resulting from different annually allocated income shares: 900, 3,000 and 6,000 euros.

ID	Budget: 900			Budget: 3,000			Budget: 6,000		
	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

5.2.5.2 Energy prices

Figure 31 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 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.



	cumulated asset	total investment	energy expediture	maintenance expenditure	residual value	net
ID 1	37079	-6820	-8161	-7088	394	15404
ID 2	37079	-11087	-54483	-2245	1123	-29613
ID 3	37079	-11768	-69232	-1566	1034	-44453
ID 4	37079	-29519	-47834	-2065	7094	-35245
ID 5	37079	-7233	-28139	-6179	436	-4036

Figure 31: Net present value of building's cash flow, considering higher energy price scenario (due to CO2 taxes) - building 1 to 5.

5.2.5.3 Renovation costs

Table 18 presents a sensitivity analysis of how the calculated optimum timing may change in two renovation cost scenarios: constant renovation costs and annual renovation cost decrease 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 18: Comparison of the optimum year resulting from the two variants: constant renovation costs and decreasing renovation costs

ID	Constant renovation costs			Decreasing renovation costs		
	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

5.2.6 Discussion

The developed method has a primary goal to calculate the optimum timing when each step in a staged renovation approach should be performed, giving a more concrete time horizon perspective when the building's decarbonisation targets set for 2050 can be met. To that aim, the model maximises the net present value of a household's energy-related cash flow. 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. The model is based on a pillar of four different aspects:

1. budget restrictions (based on households' allocated income for energy-related expenditures and, if available, loans or incentives);
2. building material ageing processes;
3. building roadmaps and investment costs;
4. interdependency between the retrofitting stages.

Discussion about the appropriate metrics to assess energy savings and the time of heating system replacement:

The results presented the comparison between two different constraints: "dependency" and "no dependency", regarding the sequence when each step should be performed. From this comparison, two relevant topics can be 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 are 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. The model confirmed this assumption by performing the heating system replacement as the last step in all variants with "dependency" between the sequence. In the "no dependency" variant, no pre-defined condition regarding the sequence is foreseen, and the model could decide even if a step should not be performed. The effect of this constraint became more evident in Building 4 for which Step 3 was not performed (in the variant with "no dependency") or was performed very late (in the variant with "dependency"); consequently, a better energy performance would not be achieved.

Discussion about the compared retrofitting approaches:

The results also presented the comparison between the single-step and the step-by-step approaches. A simplified assumption was made: the single-step is performed when homeowners have saved 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. The single-step approach is preferable if the retrofitting is performed as soon as possible; however, this is not always possible due to budget restrictions. But, if government subsidies are available, the timing of each stage may be sped up, or even the single-stage may be the preferred approach.

Discussion about the sensitivity analysis:

The sensitivity analysis investigated how the model results vary according to the following parameters: available budget, energy prices, and renovation costs. The sensitivity analysis of the available budget showed that the model is quite sensitive to the allocated budget (represented in the model as an income share) as a relevant decision variable for defining the optimum timing. On the other hand, a higher allocated budget does not necessarily mean earlier optimum timing because the optimum timing is also related to the building material ageing process. A variation in the energy prices did not directly affect the optimum timing because all energy carriers had an increase and not only one of them; however, it affected the net present value. Finally, the renovation investment cost decrease over the optimisation period generated anticipation of the steps, which was 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.

Applicability:

On the one hand, the developed model can be used by energy auditors to automatically define the optimum timing of each step when developing individual building renovation roadmaps. On the other hand, 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.

5.3 Case studies

5.3.1 Spain, Germany and Sweden: cost and climate optimality of different energy efficiency measures

The results are divided into the following parts: the first part (section 6.3.1.1) presents global costs and, consequently, the cost-optimal variants for all 16 variants in the three countries, Germany, Spain and Sweden. The second part (section 6.3.1.2) presents exemplary optimised roadmaps for the cost-optimal variant. Finally, third part (section 6.3.1.3) presents the results of the total optimised time and cumulative CO_2 emissions.

5.3.1.1 Cost-optimal variant

Figure 32 shows the global costs of each energy efficiency variant (Table 11) and is represented below by the IDs 1 to 16 for each country Spain, Germany and Sweden. The global costs consist of the specific initial investments (euro/m²) plus the specific discounted running costs (euro/m²) for space heating – defined according to Equation 18. The ID 2 is the cost-optimal variant in all three countries, with respectively 441 euros/m² (Spain), 723 euros/m² (Germany) and 789 euros/m² (Sweden). The cost-optimal variant presents 15 cm of external wall and floor insulation, 20 cm of roof insulation and a windows U-value of 0.95 W/m²K, showing that in all countries, roof insulation and highly efficient window replacement are the most cost-effective measures. ID 16 is the most energy-efficient variant, which presents a 20 cm external wall, 20 cm floor insulation, 25 cm of roof insulation and a windows U-value of 0.95 W/m²K.

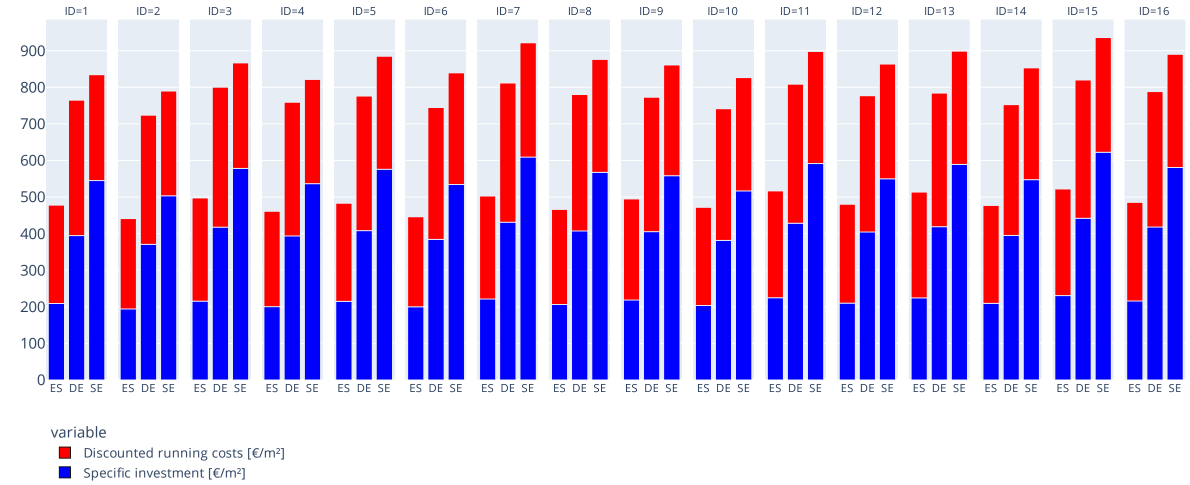


Figure 32: Specific global costs (initial investments and discounted running costs) per variant with ID 1 to 16 for Spain, Germany and Sweden

Figure 33 shows the relationship between specific initial investments and global costs. In all countries, this correlation is linear. Spain is the country with the lowest costs (both initial investment and global), while Sweden has the highest. In all countries, ID 2 is the cost-optimal, while ID 15 is the least cost-optimal.

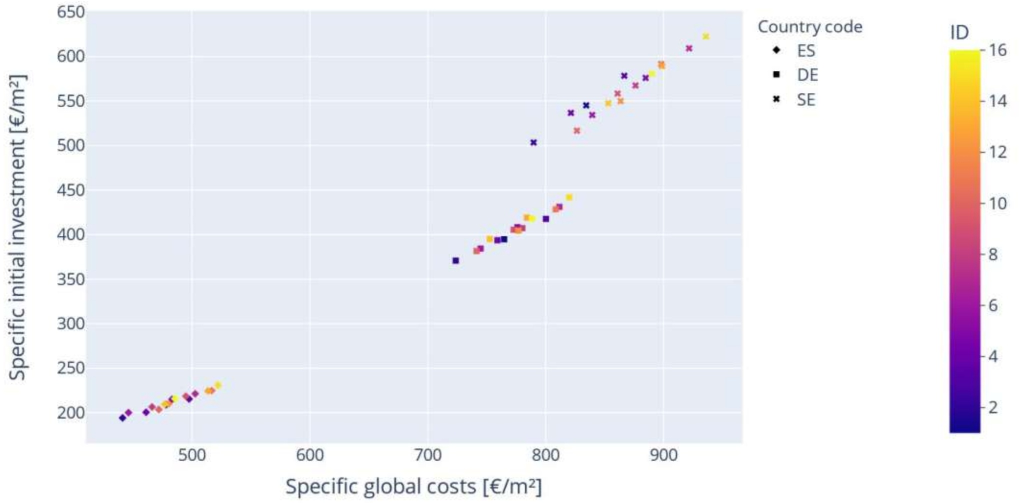


Figure 33: Specific investment costs [€/m²] versus specific global costs [€/m²] per variant with ID 1 to 16 for the countries Spain, Germany and Sweden

5.3.1.2 Optimum timing

Figure 34 shows the staged roadmaps for the cost-optimal variant (ID 2). The roadmap shows the optimised year when each stage should be performed, consequently generating a gradual decrease in the CO_2 emissions for space heating. In the optimisation model, an annual household budget of 3,000 euros is assumed to be equal for all countries.

By calculating the optimum timing, the optimisation model consequently defines also the sequence of the stages and when each stage should be performed. In general, the model defined the same sequence of measures in all three countries for the variants with the same ID. However, due to the different initial investments in each country, it resulted in different years when each step should be performed. The sequence was: Stage 1 (Roof) -> Stage 2 (Floor and heating system) -> Stage 3 (External wall and window), following the roadmap allocation suggested in Option 1 in Figure 33. The roadmaps in Spain have a lower initial investment; therefore the stages are performed earlier than in German and Sweden. However, Sweden has colder climatic conditions, a lower CO_2 emission factor due to the high share of hydro energy in the electricity mix results in lower CO_2 emissions than in the other two countries.

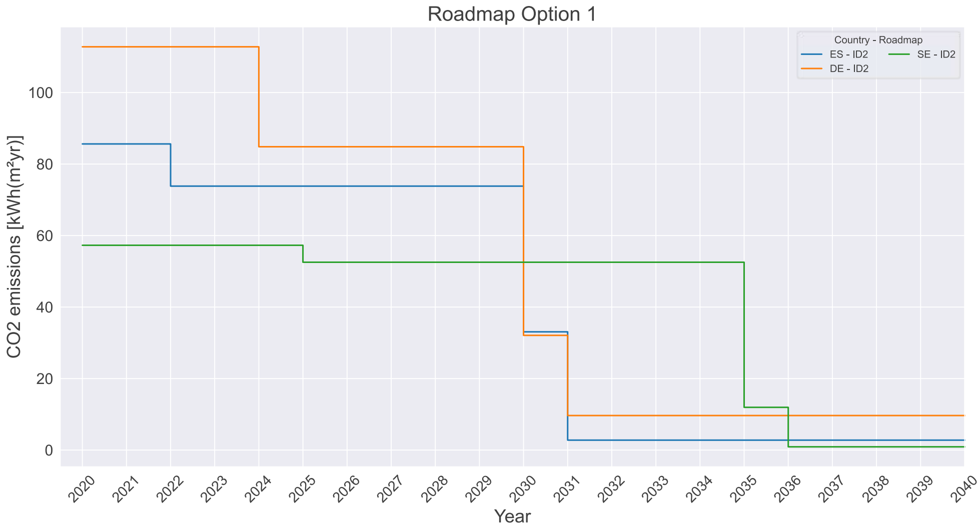


Figure 34: CO2-emission development according to the optimum timing calculated for the cost-optimal variant (ID 2) for the countries Germany, Spain and Sweden

5.3.1.3 Cumulative CO_2 emissions

Figure 35 shows the results of cumulative CO_2 emissions versus total optimised roadmap time, that is, the time between 2020 (the first optimisation year) and the last stage year. For Spain, the cost-optimal variant ID 2 is the variant with the lowest cumulative CO_2 emission (847 kg CO_2/m^2) and shortest roadmap time (11 years). For Germany, ID 6 is the variant with the lowest cumulative CO_2 emission (1175 kg CO_2/m^2) and shortest roadmap time (11 years). For Sweden, ID 6 has the lowest cumulative CO_2 emission (836 kg CO_2/m^2), however not have the shortest time. For this country, ID 2 has the shortest roadmap time (17 years). In general, the roadmaps in Germany take between 11 and 14 years, in Spain 11 and 15 years and in Sweden between 16 and 22 years. The optimised roadmap time reflects different factors: the annual household budget, the initial investments per stage, the energy prices (consequently, running energy costs) and the building's material ageing process. However, in this case, the results are closely related to the absolute initial investment costs (reflected also by the building's material ageing process) because the variables energy prices and budget are considered the same in all countries.

The roadmap time is closely related to the absolute initial investment costs, and although Spanish has lower material costs than Germany, the Spanish reference building has a bigger geometry (Table 10). In Sweden, the costs are higher than in Germany, which results in longer total roadmap times.

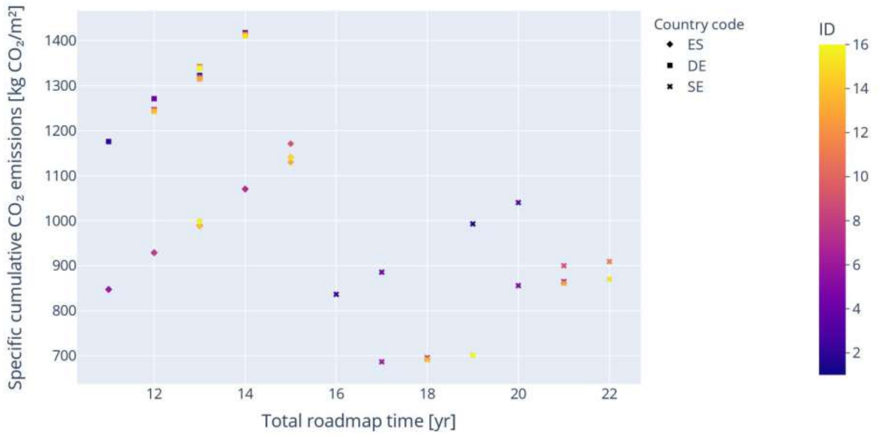


Figure 35: Cumulative CO_2 emission versus roadmap time for variants ID 1 to 16 for the countries Spain, Germany and Sweden – Roadmap Option 1 and complete renovation

5.3.1.4 Sensitivity analysis

The sensitivity analysis studies two different effects: the interrupted roadmap (based on option 1 from Figure 20), which means that instead of three, only two stages are performed (session 0). And option 2 (Figure 20), where another allocation of measures per stage is described.

Interrupted Roadmap

The interrupted roadmap consists of not performing the last stage on the optimised roadmap for Option 1 calculated by the optimisation model. Depending on the ID and country, the results show that the "Roof insulation" or "External wall insulation and Window replacement" would not be performed. Compared to Figure 35 (above), Figure 36 (below) shows that, in general, shorter roadmaps time are observed together with higher specific CO_2 emission (kg CO_2/m²). Especially in Sweden, it means a year reduction of 7 years (for IDs 12 and 16), 6 years (for IDs, 8, 10 and 14) and 5 years (for ID 6), turning them into the variants with the lowest cumulative CO_2 emission (about 750 kgCO_2/m²) and shortest roadmap time (12 years).

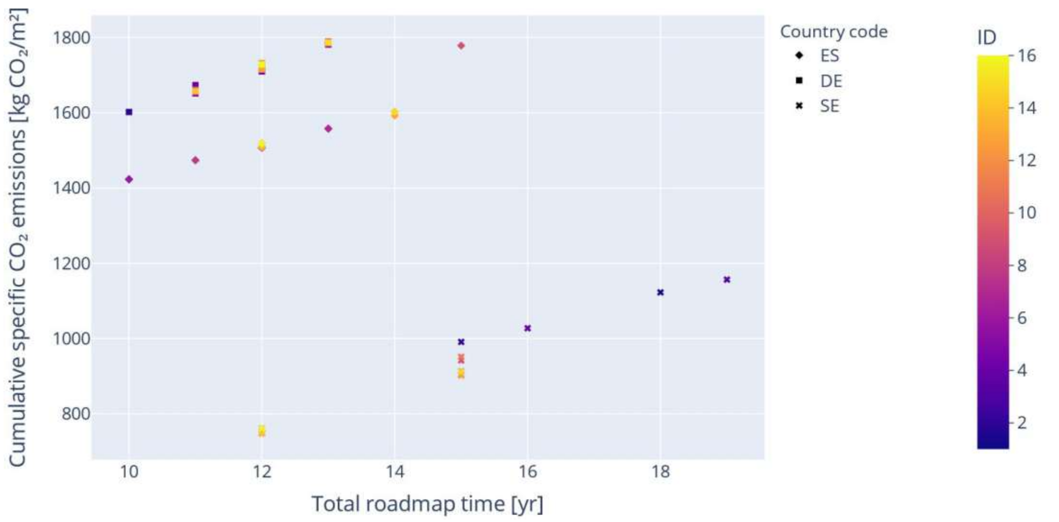


Figure 36: Cumulative CO2 emission versus roadmap time for variants ID 1 to 16 for the countries Germany, Spain and Sweden – Roadmap Option 1 and interrupted renovation

Roadmap Option 2

The roadmap Option 2 consists of allocating the measures per stage differently than Option 1, according to Figure 20. Option 2 the measure "floor insulation" in another stage. In Option 2, different from Option 1, there is an imbalance between the distribution of measures per stage, which increases the initial costs for a stage. Consequently, this increases the total roadmap time (4 to 10 years, depending on the variant) and the cumulative CO_2 emissions for all countries and variants. In all countries, ID 2 is the climate-optimal variant with the shortest roadmap time.

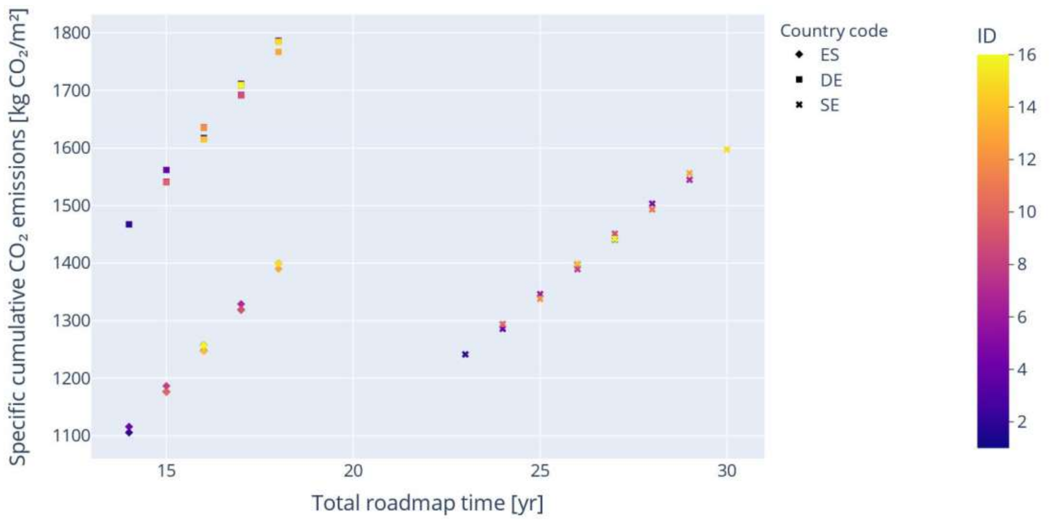


Figure 37: Cumulative CO_2 emission versus roadmap time for variants ID 1 to 16 for the countries Germany, Spain and Sweden – Roadmap Option 2 and complete renovation

5.3.2 Spain: the effect of the data-driven available budget on the optimum timing

This case study is applied for the cost-optimal variant (ID 2) according to the results presented in section 6.3.1. According to the results presented in Chapter 6.1.3, owner-occupied single-family houses represent 30% of the Spanish building stock. For this household type, the results also show that only the four and fifth income quintiles have positive annual saving. For these quintiles, the annual income is higher than 33,000 Euro/yr (see Chapter 6.1.3). For households with annual incomes below this range, renovation activities would only be economically feasible with additional incentives. Moreover, the model assumes an income share of 10% which might be annually saved for renovation activities, based on which the results are shown below.

5.3.2.1 Data-driven budget restrictions: optimum timing and net-present value

Figure 38 shows specific trends according to the construction periods of the building stock. In general, the total optimised roadmap time decreases with the annual income and is between 3 and 17 years. However, the range between the maximum and minimum roadmap time is not the same in all the construction periods: depending on the annual income, the while for buildings constructed after 2007, the optimised roadmap range is between 5 and 7 years in the construction period 1980-2006 the range is between 12 and 17 years. The net present values vary between -11,000 and 12,000 euros. The construction period between 1937-1959 presents negative net present value being the most economically unfeasible buildings due to the combination between higher energy demand and bigger geometry (consequently more initial investments). The economic feasibility affected by the annual income is especially relevant in the construction periods 1901-1936, for which renovation activities of lower annual income households are closer to net present value 0.

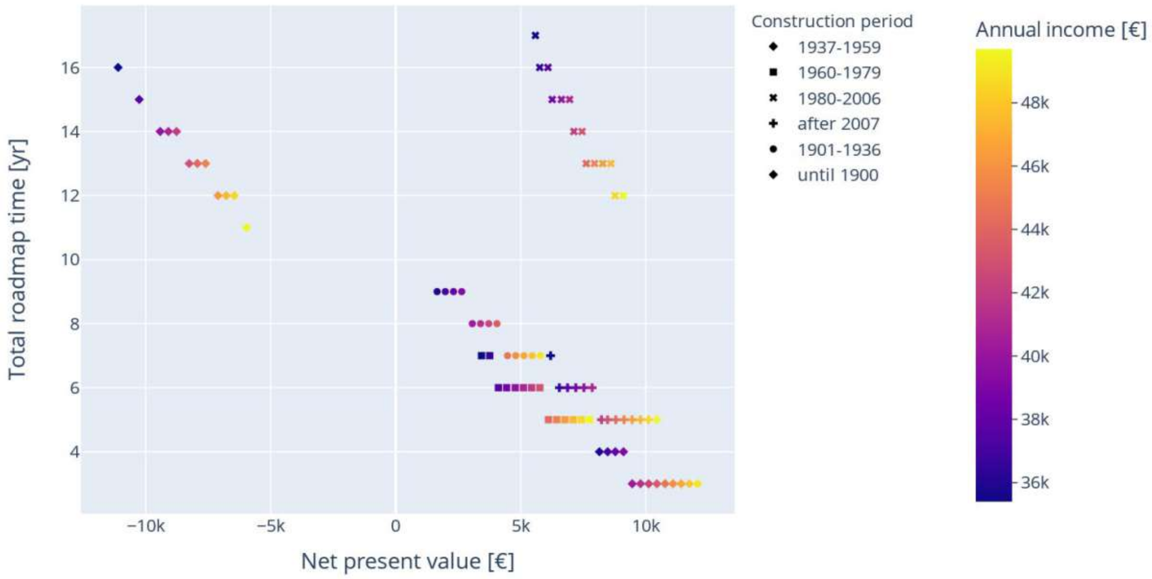


Figure 38: Optimised roadmap time versus net present value for Spanish buildings constructed between until 1900 and after 2007 and by household income class

5.3.2.2 Data-driven budget restrictions: optimum timing and cumulative CO_2 emissions

Figure 39 shows the optimised roadmap time versus the cumulative CO_2 emissions. The specific cumulative CO_2 emissions vary between 252 and 715 kgCO2/m² depending on the annual income and the construction period. The construction period after 2007 has the lowest cumulative CO2 emissions and shortest roadmap time. While the construction period 1901-1936 has the highest cumulative CO_2 emissions for lower annual incomes. For achieving the same cumulative CO_2 emissions, some construction periods require more budget than others. For example: for a cumulative CO_2 emission of about 600 kgCO2/m^2, the construction period 137-1959 requires 3,760 euros annual budget, while 1980-2006 requires 4,310 euros annual budget and 1901-1936 requires 4,360 euros annual budget mainly due to building specific geometric and technical characteristics.

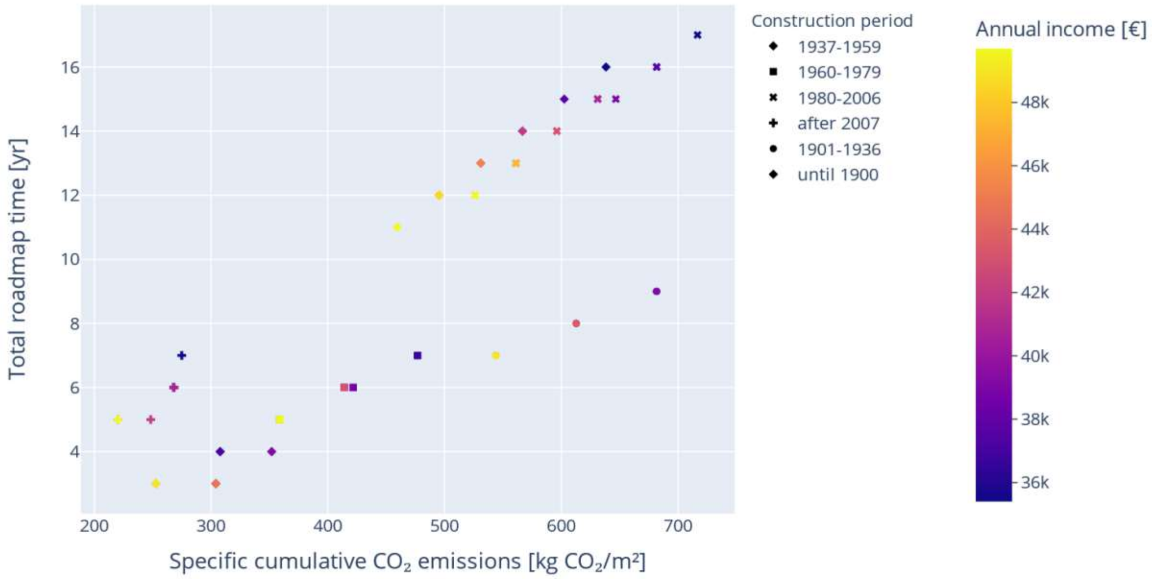


Figure 39: Optimised roadmap time versus cumulative CO_2 emissions for Spanish buildings constructed between until 1900 and after 2007

5.3.3 Discussion

The main objective of the case studies is to assess the effects of staged renovation and to derive conclusions about possibly needed adaptations on the policy instruments currently in force. The staged renovation intrinsically brings upon the time perspective of the renovation activities, being the key aspect and the main difference from the single-stage approach. The deterministic definition of roadmaps with reduced lock-in effects risks (in chapter 4.4) enabled the generation of automatised three-stages-roadmaps. The risk of lock-in effects is the main reason why, until very recently, the policy instruments have focused on single-stage renovation. However, in real life, various barriers to a single-stage renovation activity still exist, making staged renovation a commonly performed approach. Germany has good documentation on staged renovation practices, as presented by (Cischinsky and Diefenbach 2018). This study presents the depth and graduality of renovation activities. However, studies are missing in the literature that presents the timing of renovation practices to validate the present results. By using a staged renovation mixed-integer optimisation model, the time of each stage is calculated, as additionally also the cumulative CO_2 emissions. Also, the optimised roadmap time of staged renovation is quantified.

In the first case study, the main objective is the comparison between cost- and climate-optimal variants. For that, two metrics are used: “global costs”, as defined by the EPBD and currently used metric for economic assessment of renovation activities, and “cumulative CO_2

emissions", proposed as a new metric. The case study sets reference buildings of three countries in different climatic zones, Spain, Germany and Sweden and defines different energy efficiency standards for selected measures. For this comparison, the model was updated to use country-specific variables such as weather files, initial investments, primary energy factor and CO_2 emission factor.

The results showed that the cost-optimal is, in many cases, also the climate-optimal variant. For the cost-optimal variant, the second case study calculated the effect of different annual incomes (and, consequently, available budgets).

In Spain, owner-occupied single-family houses that have annual positive savings represent about 40%, representing 12% of the total Spanish households. This group has an annual income higher than 35,000 euros. The positive net present values show economic feasibility for almost all construction periods (besides 1937-1959) and annual income higher than about 31,500 euros. The calculated optimised roadmap time is between 4 and 30 years, depending on the annual income. In Spain, 70% of households are multi-family houses; then, the model should be adapted to be applied to the group.

Limitations exist, e.g. regarding the used energy demand calculation model based on the German norm DIN18599, but were also used for other countries. The calculation uncertainties could be verified by using country-wise harmonised methods as those developed and tested by the EPB standards(EPB 2020), recently also discussed by the EU-funded project U-Cert (U-Cert 2023). This, however, was beyond the scope of this paper and is left for further research.

In terms of heating system replacement measures, the present paper differs from the current economic assessments provided by MS by only considering renewable heat generation systems (i.e. heat pumps), while many studies still consider the replacement by fossil-fuel-based heating systems. It intentionally opted to do so, as the new installation of fossil-fuel-based heating systems is not in line with long-term climate and energy policy targets. Furthermore, the replacement with heat pumps was considered a replicable option, applicable in all three countries. While for example, district heating or biomass are more local alternatives.

Previous studies have discussed the model's sensitivity analysis in terms of energy prices, building owner budget restrictions and initial investment (I. Maia, Kranzl, and Müller 2021). In this case study, further sensitivity analysis presented two cases related to the staged renovation approach: first, if the roadmap is interrupted and second, another roadmap option as defined in the deterministic roadmap analysis. However, further sensitive analysis could be performed in regard to the calculated energy savings and final energy demand. To further investigate how the results are affected, the net present value changes. It means under which other conditions the net present value would become negative for each construction period.

The Russian-Ukraine war generated a rapid energy price shock. In terms of modelling, the previous studies also showed that the sequencing of staged renovation would only be affected if the energy carrier prices development have a completely different path from each other.

Meaning that, for example, electricity prices decrease, but fossil fuel prices increase. Otherwise, the roadmap sequence is maintained, and only the optimised time may be affected.

Finally, the model could be further improved in terms of automatically adjusting the annual income share to the available budget. Then, households with lower annual income may have lower shares of income to invest than higher-income households. Also, the model should include a final energy demand factor that corrects the energy expenditure according to the annual income.

6 A comparison between staged renovation in single buildings and using building stock modelling, deterministic analysis for Germany

6.1 Description of performed analysis

This case study aims to analyse the difference in the estimated energy needs for space heating between an individual building approach and a building stock model for both staged and single-stage retrofits. The workflow was carried out also to analyse the effect of various renovation cycles.

During a building life cycle, maintenance and operation activities constantly happen to avoid the first stages of degradation and failure of building elements (Flores-Colen and de Brito 2010). At the same time, usual maintenance activities and/or material replacement provides an opportunity for increasing building elements' energy efficiency and consequently improving the building's energy performance. These activities can be induced by unpredictable damages, such as breaks, leakages and cracks, or predictable parameters, such as the material's durability, which defines the material's lifetime. Because of its predictability, the parameter material's lifetime was used in the present study to determine when the retrofit measure should happen.

The envelope quality defines the energy needs for which the heating supply system should be dimensioned to cover the energy demand. Therefore, heating system replacement is a retrofit measure with limited savings potential when compared to the energy saving potential through higher building envelope energy efficiency standards. That is the reason why the indicator energy need is used. For a defined set of reference single-family buildings in Germany, the building-related data was prepared. Then, the information related to each building construction period was synchronized with the building element material lifetime by identifying the typically used construction materials (wood, cement, brick, insulation etc.) to construct each building element (windows, floor, roof, external wall).

Table 19: Reference buildings characteristics. Source: Invert-EE-Lab

Construction period	Heated area [m²]	U-value Exterior walls [W/m²K]	U-value windows [W/m²K]	U-value roof [W/m²K]	U-value floor [W/m²K]
Until 1918	142	1.7	2.8	1.3	1.0
1919 - 1948	303	1.7	2.8	1.4	0.77
1949 - 1957	139	0.9	2.6	1.1	1.0
1958 - 1968	140	1.4	2.9	0.9	1.0
1969 - 1978	147	1.2	2.6	0.6	0.8
1979 - 1983	148	0.8	4.3	0.4	0.8
1984 - 1994	146	0.7	2.6	0.3	0.5
1995 - 2001	142	0.5	1.6	0.2	0.3
2002 - 2009	147	0.5	1.3	0.2	0.3

A building element is composed of different construction material layers with thermal and other specific properties. For this study, the materials with thermal properties are on focus – as thermal mass and insulation have an influence on the energy performance of the building rather than the load-bearing materials.

Table 20 summarizes the characterization of the reference buildings, where the "x" indicates that the building element contains the specified material.

Table 20: Characterization of the reference buildings - building elements, building material and material lifetime (for each building vintage, a reference building for single-family houses in Germany). Source: own table

Building element	Middle life cycle [yr]	Measure name	until 1918	1919-1948	1949 -1957	1958 -1968	1969 -1978	1979 -1983	1984 -1994	1995 -2001	2002-2009	2010-2015
Glazing	25	multi glazing					x	x	x	x	x	x
External wall	30	ext wall insulation					x			x	x	x
Floor	30	floor with insulation				x	x	x	x	x	x	x
Roof	30	roof insulation				x	x	x	x	x	x	x
Floor	60	cellar wood (load bearing)	x									
External wall	70	ext wall cement							x			
External wall	70	ext wall wood										
Glazing	80	single glazing	x	x	x	x	x					
External wall	90	ext wall brick (load bearing)	x	x	x	x		x				
Floor	100	cellar natural stone (load bearing)		x	x							
Roof	100	roof cement reinforced										
Roof	120	roof wood chairs	x	x	x							

The characterization of the reference buildings and specification of the material's lifetime allowed the development of staged retrofitting roadmaps for each building vintage since the construction year. Assuming a strictly deterministic lifetime as specified above, the retrofitting measure's frequency is determined by the lifetime of the building material. For example, if the building element includes insulation, its maintenance activity happens more frequently than a non-insulated building element because the insulation has a comparably shorter lifetime than the other materials. Also, with the material replacement, a new life cycle starts. To make a first calibration and plausibility verification of the chosen approach, possible renovation cycles until 2017 were calculated based on the data and assumptions presented above. Table 21 below shows the number of renovation cycles per building element for two reference buildings per building vintage. The age of the building in the year 2017 is also shown.

Table 21: Building elements' renovation cycle until 2017 for each building vintage. Source: own table

Construction period	until 1918		1919-1948		1949 -1957		1958 -1968		1969 -1978		1979 -1983		1984 -1994		1995 -2001	
Construction year	1875	1918	1919	1948	1949	1957	1958	1968	1969	1978	1979	1983	1984	1994	1995	2001
Building age until 2017	142	99	98	69	68	60	59	49	48	39	38	34	33	23	22	16
Roof	1	0	0	0	0	0	1	1	1	1	1	1	1	0	0	0
Floor	3	2	2	0	0	0	1	1	1	1	1	1	1	0	0	0
External wall	2	1	1	0	0	0	0	0	1	1	0	0	0	0	0	0
Window	5	3	3	2	2	2	2	1	1	1	1	1	1	0	0	0

From the table above, it is possible to observe that buildings older than 120 years (in 2017) should have at least completed one renovation cycle of each building element (not implying to which extent this renovation measure had an impact on the energy performance of the building). Buildings of around 100 years (in 2017) still have not performed the renovation of all building elements; for example, roof renovation is still pending. Buildings with an age of 60-70 years (in 2017) only completed the window renovation cycle, according to the assumptions made. Most reference buildings constructed between 1958-1983 would have complemented at least one renovation cycle of all building elements, with the exception of the buildings constructed between 1969-1978. These buildings did not include insulation on the external walls and therefore did not complete 2017 all their first renovation cycles. In general, window replacement is the most frequent measure for all buildings. This is also in line with the findings from [30] about the empirical evidence of real-life renovation activities in Germany. Up to the construction year 1994, the buildings were relatively "young", which means that none of the building elements reached the end of their lifetime.

It is important to highlight that the frequency of the renovation cycle is not directly connected to an improvement in energy performance, as already observed by(Risholt and Berker 2013). In a study about energy performance and deep renovation trends in the German residential building stock, the authors concluded that 70-75% of old buildings did not experience an improvement in the energy performance of their building envelope (N. Diefenbach and Cischinsky 2015). To some extent, this can be explained by the fact that some building elements did not reach their end-of-life. Therefore the first renovation cycle has not been completed. On the other hand, as said above, the renovation measure can also only focus on maintenance or aesthetic reasons and thus not contribute to the energy performance of the building (e.g. plastering and painting of the façade).

After the preliminary analysis explained above, the next part of this study aims to analyse the possible effects of the staged retrofitting sequences on decarbonisation targets by upscaling the results for many buildings (Hartner et al. 2018)and also considering a single-stage approach. In the single-stage approach, a time step of 80 years was considered assumed as a complete building lifetime. Both approaches were then compared. The requirements according to the German building codes in force in the renovation year (BMUB 2016)were followed. As shown in Figure 40, the energy efficiency standards became stricter over time.

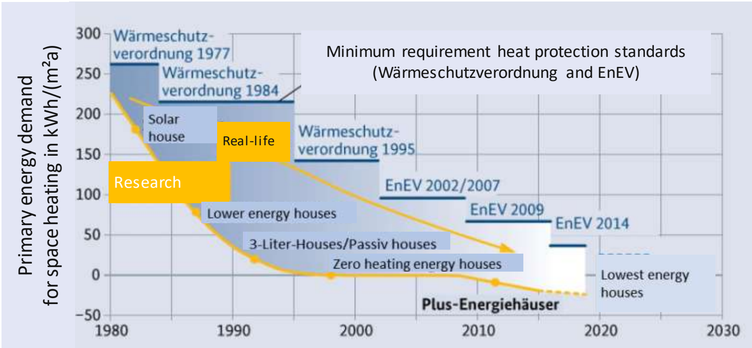


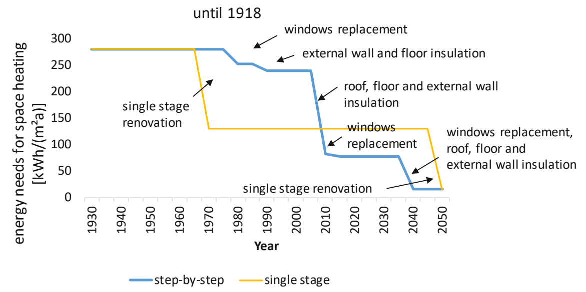
Figure 40: Development of German energy efficiency building codes. Source: adapted from [108]

The consistency of both retrofitting approaches with long-term national decarbonisation scenarios until 2050 calculated with the Invert/EE-Lab was also analysed. Invert/EE-Lab is a dynamic bottom-up discrete choice building stock simulation model. In particular, Invert/EE-Lab is designed to simulate the impact of policies and other side conditions in different techno-economic scenarios (Müller 2015). The scenarios derived from this model build on a highly disaggregated representation of the national building stock by a large number of reference buildings. Based on several parameters such as the age distribution of the building components; heat supply; distribution technologies in the building stock; and the ratio between the total costs of purchase of new components and the energy-consumption-related annual costs using the installed component, the share of buildings and components is determined. In contrast to the approach and focus of this paper, Invert/EE-Lab assumes single-stage renovation measures. The European Project SET-Nav applied current policy settings in the model Invert/EE-Lab, and the results of a scenario study showed that 77 % CO_2-Emission reduction can be achieved by 2050 (Hartner et al. 2018). This scenario was taken as a reference development for the above-mentioned comparison.

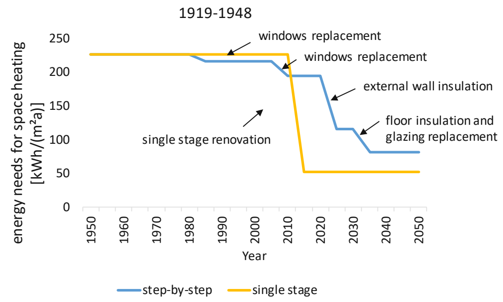
6.2 Energy needs for space heating development: staged versus single-stage retrofitting

Figure 41 shows the specific energy needs for space heating in kWh/(m²a) development from the assumed construction year (as the mean value within a certain construction period) until 2050 for each reference building. Nine reference buildings are specified in the construction period before 1918 until 2009.

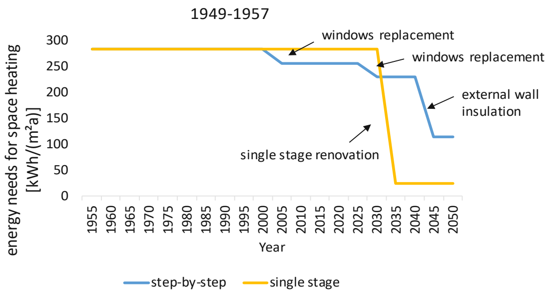
As the German heat protection legislation started in 1977 (Figure 40), only the renovation cycles that happened after this date were considered to generate an energy performance improvement. In staged retrofitting, the sequence of measures is determined according to the construction material's lifetime. In the single-stage approach, the renovation occurs at a constant frequency of 80 years (as explained above).



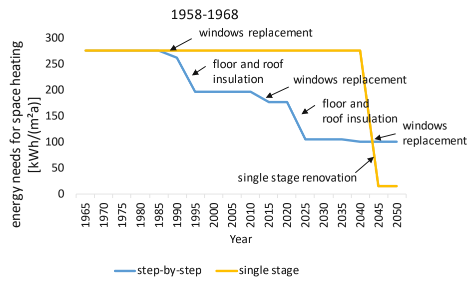
(a) until 1918



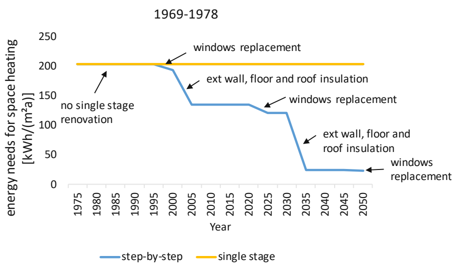
(b) 1919-1948



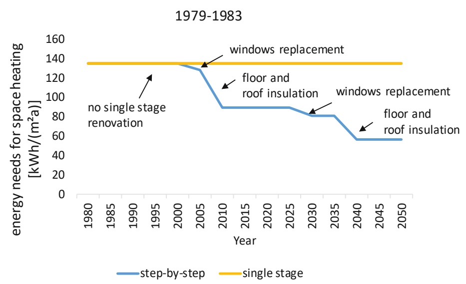
(c) 1949-1957



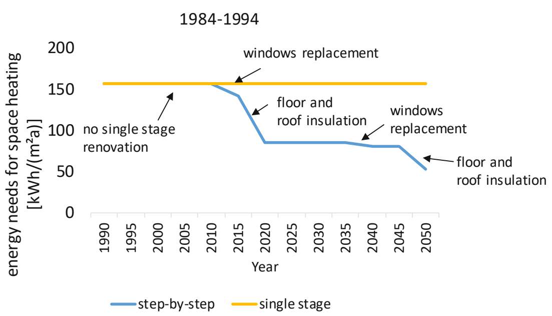
(d) 1958-1968



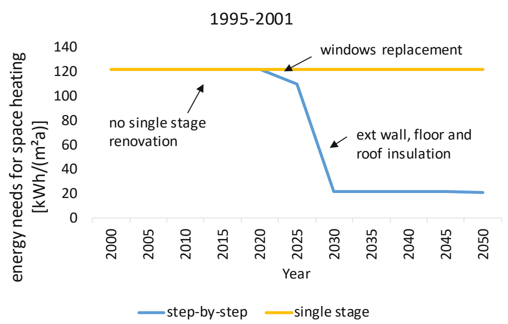
(e) *1969-1978*



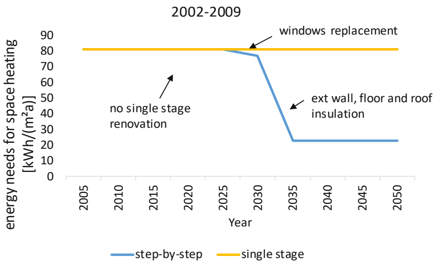
(f) *1979-1983*



(g) 1984-1994



(h) *1995-2001*



(i) 2002-2009

Figure 41: renovation sequences and development of energy needs for space heating, according to the step-by-step versus single-stage concept – reference buildings for construction vintage

- **Until 1917**

Staged retrofit: Roof (wood chairs): two thermal-relevant roof renovation cycles would happen. The first in 2010 and the second in 2040. External wall (brick): three thermal-relevant external wall renovation cycles would happen. The first in 1980, the second in 2010 and the last one in 2040. Windows (multi-glazing): three thermal-relevant glazing renovation cycles would happen. The first in 1990, the second in 2015, and the third in 2040. Floor (wood): three thermal-relevant floor renovation cycles would happen. The first in 1980, the second in 2010 and the third in 2040.

Single-stage retrofit: renovation cycles would happen two times: in 1970 and 2050.

- **1919-1948**

Staged retrofit: Roof (wood chairs): no roof renovation cycles would happen. External wall (brick): one thermal-relevant external wall renovation cycle will happen in 2025. Windows (multi-glazing): three thermal-relevant glazing renovation cycles would happen. The first in 1985, the second in 2010, and the third in 2035. Floor (natural stone): one thermal-relevant floor renovation cycle will happen in 2035.

Single-stage retrofit: renovation cycles would happen one time in 2015.

- **1949-1957**

Staged retrofit: Roof (wood chairs) and floor (natural stone): no roof renovation cycles would happen. External wall (brick): one thermal-relevant external wall renovation cycle will happen in 2045. Windows (multi-glazing): three thermal-relevant glazing renovation cycles would happen. The first in 1980, the second in 2005, and the third in 2030.

Single-stage retrofit: renovation cycles would happen one time in 2035.

- **1958-1968**

Staged retrofit: Roof (with insulation) and floor (with insulation): two thermal-relevant roof renovation cycles would happen. The first in 1995 and the second in 2025. External wall (brick): no external wall renovation cycles would happen. Windows (multi-glazing): three thermal-relevant glazing renovation cycles would happen. The first in 1990, the second in 2015, and the third in 2040.

Single-stage retrofit: renovation cycles would happen one time in 2045.

- **1969-1978**

Staged retrofit: Roof (with insulation): two thermal-relevant roof renovation cycles would happen. The first in 2005, the second in 2035. External wall (with insulation): two thermal-relevant roof renovation cycles would happen. The first in 2005, the second in 2035. Windows (multi-glazing): three thermal-relevant glazing renovation cycles would happen. The first in 2000, the second in 2025, and the third in 2050. Floor (with insulation): two thermal-relevant roof renovation cycles would happen. The first in 2005, the second in 2035.

Single-stage retrofit: no single-stage renovation cycles will happen until 2050.

- **1979-1983**

Staged retrofit: Roof (with insulation) and floor (with insulation): two relevant thermal roof renovation cycles would happen. The first in 2010, the second in 2040. External wall (brick): no external wall renovation cycles would happen. Windows (multi-glazing): two thermal-relevant glazing renovation cycles would happen. The first in 2005 and the second in 2030. The first in 2010, the second in 2040.

Single-stage retrofit: no single-stage renovation cycles will happen until 2050.

- **1984-1994**

Staged retrofit: Roof (with insulation) and floor (with insulation): two relevant thermal roof renovation cycles would happen. The first in 2020 and the second in 2050. External wall (cement): no external wall renovation cycles would happen. Windows (multi-glazing): two thermal-relevant roof renovation cycles would happen. The first in 2015, the second in 2040.

Single-stage retrofit: no single-stage renovation cycles will happen until 2050.

- **1995-2001**

Staged retrofit: Roof (with insulation) and external wall (with insulation): one thermal relevant renovation cycle would happen in 2030. Windows (multi-glazing): two thermal-relevant roof renovation cycles would happen. The first in 2025 and the second in 2050. Floor (with insulation): one thermal-relevant roof renovation cycle will happen in 2030.

Single-stage retrofit: no single-stage renovation cycles will happen until 2050.

- **2002-2009**

Staged retrofit: Roof (with insulation), external wall (with insulation) and floor (with insulation): one thermal relevant roof renovation cycle would happen in 2035. Windows (multi-glazing): one thermal-relevant roof renovation cycle will happen in 2035.

Single-stage retrofit: no single-stage renovation cycles will happen until 2050.

Table 22 shows a summary of the last renovation (staged and single-stage retrofit).

Table 22: Last renovation year for each reference building and retrofit approach (staged and single-stage retrofit)

Building vintage		**until 1918**	**1919 - 1948**	**1949 - 1957**	**1958 - 1968**	**1969 - 1978**	**1979 - 1983**	**1984 - 1994**	**1995 - 2001**	**2002 - 2009**
Construction year of reference building		**1890**	**1935**	**1955**	**1965**	**1975**	**1980**	**1990**	**2000**	**2005**
Step-by-step	**Roof**	2040	no renovation	no renovation	2025	2035	2040	2050	2030	2035
	Floor	2040	2035	no renovation	2025	2035	2040	2050	2030	2035
	External Wall	2040	2025	2045	no renovation	2035	2050	no renovation	2030	2035
	Window	2040	2035	2030	2040	2050	2030	2040	2050	2035
Single stage	**all building elements**	2050	2015	2035	2045	no renovation	no renovation	no renovation	no renovation	no renovation

Figure 42 shows the three values of specific energy needs in kWh/(m²a) per construction year: the status quo (without any measure) and after retrofitting through both staged and single-stage approaches. Also, the energy savings [%] achieved by both concepts are shown above each column.

For buildings constructed before 1968, the single-stage presents more energy savings because these buildings were constructed with materials that have a long lifetime. For buildings constructed after 1979, the single-stage would be performed due to the short material lifetime. Then, the most critical construction period was "1969-1978", as it was already constructed with materials with shorter lifetimes (e.g. insulation); in the staged retrofitting, all building elements would be improved at least once. However, in the single stage, no measure would be performed.

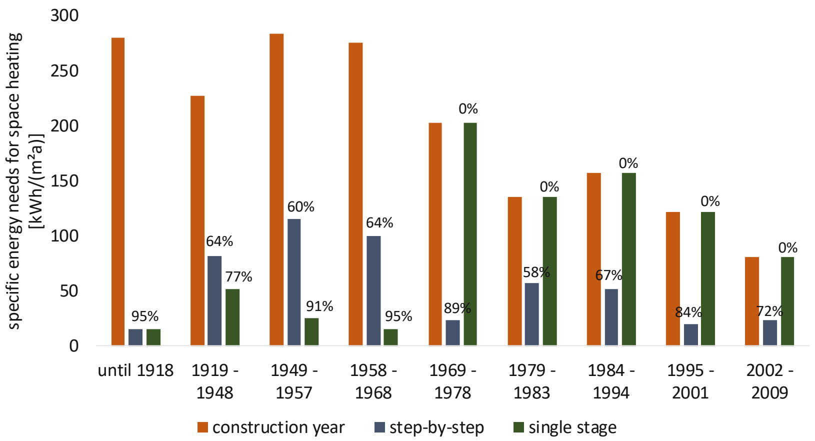


Figure 42: Energy needs (before and after renovation) and energy savings according to both staged and single-stage retrofit for each building construction period.

6.3 Energy needs for space heating: staged and single-stage retrofitting and building stock model

Figure 43 shows the comparison of specific energy needs for space heating in kWh/(m²a) between the staged and single-stage retrofit and the model Invert/EE-Lab for each reference building. Regarding the Invert/EE-Lab results, the figure shows the average weighted energy needs for space heating and its ranges. Both approaches present results between the Invert-EE/Lab model's ranges, which confirms the plausibility of both approaches. The range of energy needs in Invert-EE/Lab results reduces with the construction period. In general, the stage-retrofit present closer results to the Invert-EE/Lab, especially in the construction periods "1919-1948", "1949-1957", "1958-1968", "1979-1983". The construction period "1969-1978" presents a high discrepancy, where both approaches contrary differ from the mean. The construction period "until 1918" has the most similar results in both approaches.

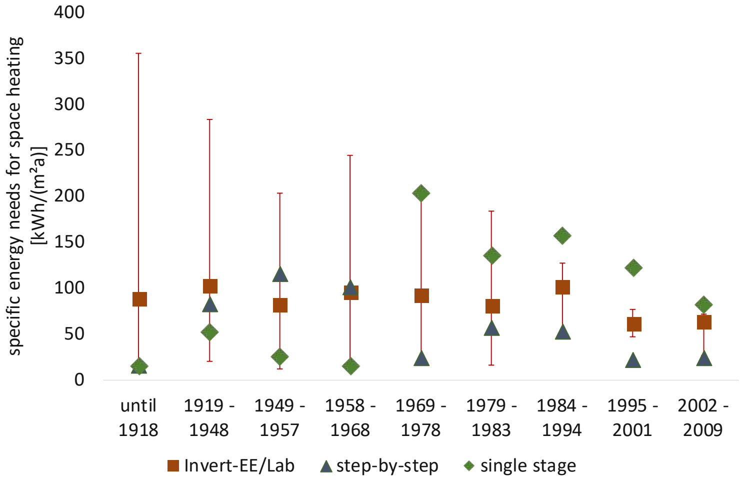


Figure 43: Comparison of specific energy needs for space heating in kWh/(m²a) between step-by-step concept, single stage concept and Invert/EE-Lab model, for a reference building of each building vintage (before 1918 until 2009)

After the specific energy needs for space heating for the reference buildings had been calculated, they were up-scaled to a building stock level. The total energy needs for space heating in TWh/a in 2050, according to each concept, is 122 TWh/a (Invert-EE/Lab), 81 TWh/a (staged-retrofit) and 140 TWh/a (single-stage). Figure 44 shows the comparison of total energy needs for space heating TWh/a between the staged and single-stage approach and the Invert/EE-Lab model for each building vintage (before 1918 until 2009). Further conclusions are discussed in the next chapter.

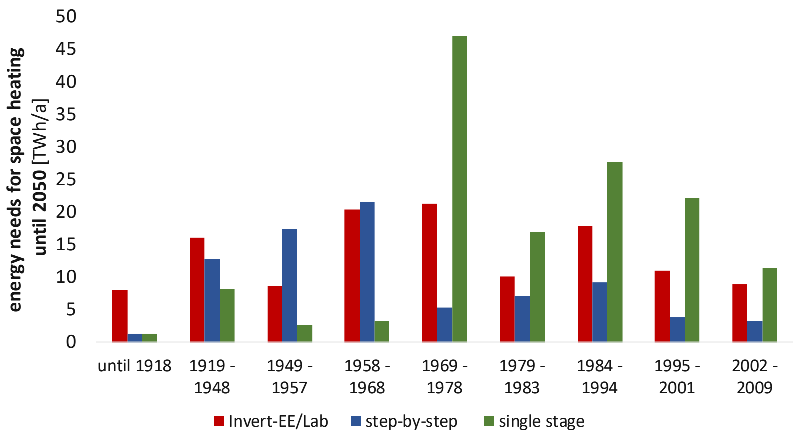


Figure 44: Comparison of total energy needs for space heating TWh/a between step-by-step concept, single stage concept and Invert/EE-Lab model for each building vintage

6.4 Conclusions and key-learnings

The first conclusion refers to the staged approach. Buildings constructed until 1957 present a wide range of material`s lifetimes (25 to 120 years), which means that it takes longer until all building elements have been completed at least one renovation cycle. In the construction periods of 1958-1968 and 1979-1983, the material lifetime range is lower (25 to 90 years). The buildings constructed from 1995 present a shorter interval until at least one renovation cycle has been completed (25-30 years) because these buildings' external walls, roofs and floors were constructed from the beginning with insulation layers. This implies that in non-insulated building elements (external walls, roof and floor) after the first renovation cycle was completed, the subsequent renovation cycles happen more frequently because of the addition of an insulation layer and its short lifetime. In terms of renovation sequences, the building construction year was an important parameter to define the time analysis of future measures and, therefore, the projection of the energy needs for space heating.

The comparison between both retrofitting approaches showed that buildings constructed before 1969 presented higher energy savings with the single-stage approach than with the staged one. Buildings constructed after 1969 would not go through any single-stage retrofit until 2050, so up to 1969, the staged approach presented higher energy savings. These results are highly connected with the assumption of the building lifetime of 80 years for the single-stage approach.

In general, the applied and analysed approaches delivered different results: due to the fact that insulated building elements have shorter renovation cycles than non-insulated ones after the first thermal renovation cycle, the staged renovation leads to a faster adaptation of the building elements to the building code in force. On the other hand, in the single-stage approach, the building's energy performance remains the same over a longer period of time. Also, in the single-stage approach, the renovation time step is determined by the building's lifetime, which means that by the time of the renovation, a building element might not have reached its end of life.

Overall, for the year 2050, the results show that the analysis of both thermal renovation approaches, staged and single-stage present plausible results when compared to the Invert-EE/Lab Model. When upscaling the specific energy needs for space heating from a single reference building to the national building stock level, the distribution of buildings, in terms of the number of buildings and their different energy needs, becomes a relevant parameter. The Invert-EE/Lab Model calculates a wide range of energy needs for space heating, where older buildings present a wider range than newer ones. In terms of total energy needs for space heating (TWh/a) in 2050, the staged-retrofitting approach resulted in lower energy demand than the single-stage approach. Especially because the first leads to the deep renovation of some building elements in buildings constructed after 1969 (middle-aged and younger buildings). Contrary to these second, where buildings constructed after 1969 would not perform any deep renovation, although some of them present higher energy needs (for example, building vintage 1969-1978, 203 kWh/m²a).

Limitations of this study are related to the reference buildings (described according to the chosen database) and other assumptions regarding building elements and components. Also, that is a deterministic analysis, where the assumptions a decisive in the results. Further sensitivity analysis should be done, for example, shorter building time in the single-stage approach.

Another point is the consideration of the building code for existing buildings. It was assumed that with time, benchmarks for existing buildings follow the same threshold as for new buildings, and the construction activities strictly follow the codes, which is, in real life, not the case. This assumption, however, influences the achieved energy needs. Therefore further sensitivity analysis will include other retrofitting targets. Also, the economic consequences of not reaching materials end-of-life should be taken into account by defining the time step of the single-stage concept.

The conclusions from this analysis drove into the thesis as follows:

- This case study allowed a better understanding of the effects of the material lifetime. Then, the staged-renovation optimisation model replaced the deterministic assumptions with a more realistic distribution of the building elements´ lifetimes using a Weibull distribution.
- In regard to the residual value, using the net present value as an indicator to be maximized in the objective function allows the integration of the residual value of the initial investment into the calculation (discussed as a limitation of the case study).
- The building roadmaps studied considered not only single enveloped measures but the combination of them in a single stage. This also reduces the number of stages performed and increases the energy-saving potential per stage.
- The empirical evaluation of the historical renovation cycles is in real-life activities very dependent on the building owner and the available budget. A building owner may perform only one renovation cycle per building element, as long as not forced to, through damages or material failure even though this will depend on the available budgets and necessary investment costs. Therefore, this was considered an important aspect to be further analysed in this thesis.

7 Synthesis of highlights and limitations

Below are the summarised highlights (section 7.1) and limitations (section 7.2) of the work.

7.1 Highlights

The following highlights sumarise the present work:

- **Modelling**:
    - Development and testing of a mixed-integer optimisation model for staged retrofit to calculate the optimum timing of each stage based on techno-economic parameters.
    - Development of a robust method to statistically match EU-SILC and HBD datasets via logistic regression (accuracy higher than 77%).
    - Use data-driven model assumptions and input data regarding available household budgets besides arbitrary assumptions.
- **Analysis:**
    - Comparison between cost- and climate optimality of different energy efficiency measures using the well-established metric global costs and the metric of cumulative CO_2 emissions not yet mentioned in the EU Energy Performance of Buildings Directive (EPBD).
    - The metric cumulative CO_2 emissions represent both depth and time perspective of renovation activities, thus being the most adequate to assess the progress of EU's building stock decarbonisation.
- **General insights**:
    - To better assess the time perspective of renovation activities, it is necessary to extend the current building typology semantics to the techno-economic classification of households, considering dwelling type and ownership status to better represent building stock's heterogeneity when modelling renovation activities.
    - The classification of households according to techno-socio-economic characteristics increases the efficiency and effectiveness of the policy and financing schemes and, consequently, renovation activities by carrying out a more end-user-targeted approach.
    - The total optimised roadmap time can vary between 5 and 17 years and depends on buildings' techno-geometric characteristics and the available household budget.
    - Staged renovation may lower cumulative CO_2 emissions if performing the single-stage renovations later. Then, a well-coordinated mix of renovation activities enable the decarbonisation targets.
- **Insights Spain 2015**:
    - 16% of the households spend more than 600 euros annually on natural gas (Data for Spain 2015)

- Natural energy expenditures are alone not a trigger to renovate, showing the need for end-user targeted financing and incentives schemes.
- Rented single-family houses are the most vulnerable household types due to their low income and saving.
- Owner-occupied single-family houses have the highest natural gas expenditure showing the highest energy-saving potential.

7.2 Limitations

For a proper interpretation of the present work's results and further analyses that build on the developed methods, one should be aware of the limitations listed below. These limitations are also recommendations for future research going beyond the scope of the work in this thesis:

- **Statistical matching modelling**: the model implemented in R cannot be easily re-used and needs to be adapted before. Especially the comparison of variables and selection of matching variables should be verified.
- **Insights Spain 2015:** update with 2020 HBS data, which was unavailable during this part of the present thesis.
- **Automatised generation of roadmaps:** the energy demand calculation based on the German norm DIN18599 may include uncertainties (for example, over-estimated savings). Meaning that the results may calculate under-estimated roadmap time due to over-estimation of energy savings. Then, a verification should use country-wise harmonised methods developed and tested by the EPB standards (EPB 2020).
- **Mixed-integer optimisation model for staged retrofit optimum timing:**
    - It should be adapted to other household types, for example, multi-family houses privately rented, as other aspects relevant for these household types may also influence the optimal timing of renovation measures. For example, tenants' age and life situation and the landlord/tenant investment split dilemma.
    - Not considering the over-sizing factor of heating systems (which would impact the heating system's efficiency) is considered a relevant limitation of the model. However, this topic is left for further research since the existing literature does not provide sufficient evidence.
    - Additional investment for site preparation (including scaffold) per renovation stage are especially relevant when comparing single-stage and staged-renovation. Then, future work should include these additional investments besides material and labour costs.
    - The dynamic actualisation of energy prices can substitute the energy price scenarios used as input data. Also, the databases could include dynamic CO2 factors due to the increasing share of renewable energies in the electricity mixes.

8 Conclusion and policy recommendations

Until recently, policy instruments have focused on the single-stage building renovation approach for two main reasons. Firstly, such an approach allows for fast CO_2 emission reduction once retrofit occurs. Secondly, the risk is lower in interrupting the process or committing technical mistakes that affect the buildings' energy performance. In 2018, the policymakers recognized that the staged renovation approach is widely performed in real-life renovation practices and introduced it in the recast of the Energy Performance of Buildings Directive (EPBD) 2018/844/EU. Although expert opinions still diverge regarding the staged renovation approach, developing more studies about it, its technical burdens on the implementation, the homeowner's conditions to perform it, and its effects on achieving EU's decarbonisation targets will enrich the actual state of knowledge. In addition, the Russian-Ukrainian war that started in 2022 sped up the process of the natural gas phase-out, expressly to guarantee reduced fuel dependency. In this context, possible measures for reducing fuel dependency are building renovations and increased energy efficiency.

The staged renovation concept is under-explored in the literature. In this context, the present work explores two different areas: 1) the end-users decisions as well as triggers and barriers to renovate, especially concerning time and budget availability and 2) the technical aspects, especially regarding the implementation of measures as lock-in effects, inter-dependency of measures, a combination of measures and sequence of them.

This thesis contributes to the current state of research by demonstrating a methodology to statistically match EU-SILC and HBS data sources and to generate a techno-socio-economic synthetic dataset. The results contribute to the first discussion area described above. The generated dataset allowed deriving data-driven budget assumptions for the optimisation model stead of arbitrary assumptions. This study considers for different household types using data from Spain in 2015. First insights from the statistical analysis discussed household economic situations and natural gas consumption as a trigger for possible renovation activities. The results show that classifying the households' types by dwelling type and ownership status better represents the building stock's heterogeneity. The results allow classifying energy-poor households and "able-to-pay" for retrofitting households, increasing the efficiency and effectiveness of policy and incentive schemes. 12% of Spanish households are owner-occupied single-family houses with income higher than 35,000 euros annually that could afford renovation activities. This group has the highest natural gas expenditure. Rented single-family houses are the most vulnerable due to low income and savings. The data showed that 16% of the households spend more than 600 euros annually on natural gas, which is considered high expenditure; however, reducing this natural gas expenditure is not considered a trigger to renovation. These results and conclusions answer the first research question.

Another contribution to the current state of research is the staged renovation mixed-integer optimisation model implemented as Python programming code based on techno-economic parameters. This model delivers the optimum timing by maximizing the net present value. The net present value represents the household's energy-related cash flow, including available budget and energy-related expenditures. Real-life roadmaps provided by the EU H2020 iBRoad project allowed testing the model during the development phase. The discussion comprised two aspects of the stage retrofits: the combination of measures per stage (considering both envelope and heat supply system measures) and the sequence to perform each stage. An energy auditor can define the combination of measures (in the real-life tailored roadmap) or can be simplified in an automated workflow. First, the optimisation models calculated the optimum time to perform each stage. Then, the comparison between two contraints allowed investigating the sequence of each stage: the free decision of measures sequence (called independent) or forced decision (called dependency), where the last stage is the one with the heating system supply. Based on the comparison between these variants, the discussion included two relevant topics: the sequence of performing the steps in terms of oversized heating supply systems and the appropriate metrics to assess energy savings of staged retrofits. Higher cumulated energy savings resulted when the model freely decided about the stage sequence and was not forced to replace the heating system last. The justification for replacing the heating system as the last step is avoiding oversized operation, as all enveloped measures would happen before. However, the case of free decision is closer to real-life renovation activities where homeowners often change the heating system before performing other envelope measures. If done correctly, the heating system replacement may generate energy cost savings that could economically enable the performance of other measures These results and conclusions answer the second research question.

In the second phase of the work, the optimisation model was used in different cases to provide insights about staged retrofits and their impacts on building stock decarbonisation. A calculation module that generates automatised three-stages roadmaps was coupled to the optimisation model, allowing the study of two cases. The first case study compared cost- and climate-optimal energy efficiency variants for three countries: Spain, Germany and Sweden. As the main result, the cost-optimal variant (indicated through the metric "global costs") was, in many cases, also the climate-optimal (indicated through the metrics "cumulative CO_2 emission). The second case study combined different results. For the case of Spain and the cost-optimal variant, data-driven annual income (and consequently available budget) was used to assess available budgets. Also reference buildings represented the Spanish building stock. Generally, the total optimised roadmap time decreases with the annual income between 3 and 17 years. However, the range between the maximum and minimum roadmap time is not the same in all the construction periods: depending on the annual income, the while for buildings constructed after 2007, the optimised roadmap range is between 5 and 12 years in the construction period 1980-2006 the range is between 12 and 17 years. The net present values vary between -11,000 and 12,000 euros. The construction period between 1937-1959 presents negative net present value as the most economically unfeasible buildings due to the combination of higher energy demand and bigger geometry (consequently more initial investments). The economic feasibility affected by the annual income is especially relevant in the construction periods 1901-1936, for which renovation activities of lower annual income households are closer to net present value 0. The specific cumulative CO_2 emissions vary between 252 and 16,100 kgCO2/m² depending on the annual income and the construction period. The construction period after 2007 has the lowest cumulative CO2 emissions and shortest roadmap time. While the construction period 1901-1936 has the highest cumulative CO_2 emissions for lower annual incomes. For achieving the same cumulative CO_2 emissions, some construction periods require more budget than others. For example, for cumulative CO2 emissions of about 600 kgCO2/m2, the 1960-1979 construction period requires 28,800 euros, while 1980-2006 requires a budget of 47,500 euros. These results and conclusions answer the third research question.

Model sensitivity analysis in terms of energy prices, available budget, interest rate, initial investments, interrupted roadmap and different roadmaps were performed and demonstrated that some parameters affect the sequence of the roadmaps (i.e. distribution of initial investments between the stages). In contrast, others affect the range of net present value (i.e. energy price when the energy carry prices have the same development).

Finally, a comparision with building stock models demonstrated how to possibly validate the results in Chapter 6. Ideally, the empirical data should validate the results, howver The literature review showed that empirical evidence of real-life renovation activities does not include the time perspective.

To conclude, the choice between staged versus single-stage renovations depends on the timing: single-stage renovation only generates low cumulative CO_2 emissions when performed earlier. At the same time, a staged renovation can present lower cumulative CO_2 emissions over time. Both depend on the initial investments and the building owner's budget. Staged renovations have the advantage of being faster and adaptable to the building code in force. Also, the single-stage approach defines randomly when the time to undergo the renovation. Meaining that renovation undergone before the building material building material has not reached its end-of-life, have higher residual values from the initial investments.

Considering that in the whole building stock, immediate and early single-stage renovation is not feasible for all buildings at the same time, a well-coordinated mix of fast single-stage renovation measures and staged renovation is ideal for reducing buildings’ CO2 emissions. Thus, adequately planned renovation approaches are essential, which creates the need for renovation passports (BRPs) and operability between building-related datasets through Building Logbooks.

Increasing the building retrofitting activities is a multi-disciplinary task that reflects the interaction of different areas, not only depending on technical aspects. Market structures include the construction of new buildings; demolition rates; energy prices, including CO_2 taxes; the availability, skill, and labour costs of installers; technology initial investments and availability on the market; the availability of innovative technologies such as prefabricated building elements for renovation activities (external walls/façade, roofs, etc.); inflation; ownership-structure and building real estate transactions; household’s profiles, etc. Then, for a successful space heating decarbonisation, a mix of measures that reduce the buildings' energy demand and diversify the heating supply system is needed, together with supporting homeowners in the implementation (i.e. One-Stop-Shops, pre-fabricated solutions end-user targeted financing and incentive schemes).

In the context of the present work, the policy recommendations are:

- Building renovation passports should include more specific definitions of the staged renovation, including, for example, a maximum number of planned stages or the minimum energy performance per stage, considering the risk of interruption.
- The time perspective and depth of renovation activities should also be represented by a metric as cumulative CO_2 emission. This metric is also currently used in the climate report produced by the Intergovernmental Panel on Climate Change (IPCC). Its introduction would improve the evaluation of decarbonisation progress - currently defined by the Member States in their long-term renovation strategies (LTRS).
- The development and market penetration of new tools that properly plan the staged retrofit and provide time-specific time estimation, consequently, how fast the decarbonisation targets for 2050 happen.
- Retrofits are vital for building stock decarbonisation, as they reduce buildings' energy demand, consequently reducing the needed supply. However, increased retrofitting rates will only be possbile through massive financial support. Therefore, public authorities should initiate and drive these activities, and private-public cooperation should finance end-user-targeted schemes.
- There is a need for end-user-targeted incentive schemes to increase policy effectiveness, as space heating decarbonisation requires heterogeneous solutions. To improve accuracy in defining financial incentives and mobilised investments, retrofitting end-user's profiles should be defined based on techno-socio-economic characteristics such as ownership status, marriage status, age, etc.
- From the financing perspective, attractive interest rates, innovative financing schemes, and more incentive programs are innovative solutions. The national long-term renovation strategies (LTRSs) are an appropriate policy instrument where Member States can better frame the financial conditions for retrofitting activities.
- Existing instruments such as One Stop Shops and EPC databases should be motivated to support end-users and policymakers to find the best strategy for decarbonising a single building and a building stock. Quartiers and municipal initiatives should also be encouraged.

As future work and follow-up activities that build on the present thesis are:

- Extend the stage retrofit optimisation model and the analysis to other building typologies (privately rented or socially rented multi-family houses) while cross-cutting these typologies with more specific homeowner affordability profiles.
- Extend the model's objective function into a multi-objective optimisation model and include a CO_2 emissions minimisation.

- Perform more analyses to investigate the optimal roadmap for the same building, which means the optimal combination of measures per stage and the optimal number of stages per building. Extend the list of renovation measures.
- Allow the model to consider the economic effects of the interdependency of stages under the consideration of full and partial load operation. The current literature review did not identify many studies that focus on this economic quantification; however these literatures are especially relevant for cases where the heating system replacement is the first measure performed without improving the building envelope quality.
- Improve the current state of renovation data: evidence from real-life practices can be improved Europa-wide, and longitudinal data collection would improve model validation. For example, some energy agencies have documentation about building energy advice; however, there is still a gap in information about performed measures.
- Explore the generated synthetic dataset and extend it with both more variables or match with other existing datasets (as, for example, EPC databases), also updated according to subsequently launched HBS and EU-SILC survey campaigns.
- Extend the dataset to other countries and years, especially the updated HBS and EU-SILC survey campaigns.
- Implement an automatically adjusted available budget according to the annual income share. Then, households with lower annual income have lower shares of income to invest than higher-income households.
- Implement a final energy demand factor that corrects the energy expenditures according to the annual income, assuming that low-income households have different energy consumption behaviour than higher-income ones. The interpretation of the results for Spain 2015 led this conclusion.

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10 Figures

11 Tables

12 Equations

13 Appendix I: Overview publications and scientific contributions

This PhD thesis is based on the following scientific contributions:

I. Published journal publications:

I.Maia, L. Kranzl, and A. Müller, “New step-by-step retrofitting model for delivering optimum timing,” *Appl. Energy*, vol. 290, p. 116714, Aug. 2021, doi: 10.1016/j.apenergy.2021.116714.

I.E. N. Maia, R. M. Moraes, R. T. Almeida, L. Kranzl, A. Müller, and F. Schipfer, “Integration of datasets to provide insights about households’ natural gas expenditure as trigger to building stock decarbonisation,” *Heliyon*, vol. 9, no. 4, p. e14922, Apr. 2023, doi: 10.1016/J.HELIYON.2023.E14922.

I.E.N. Maia, D.Harringer, L. Kranzl, and A. Müller, “Staged retrofit and the time perspective of renovation activities: which other metrics could be used to assess building stock decarbonisation”, Smart Energy, accepter with major revision (under review, deadline 3.5.3023)

II. Peer-reviewed conference papers:

7th Internal Building Physics Conference (IBPC 2018). I.Maia, L. Kranzl, A. Müller, M.Hartner,S.Forthuber. “Techno economic analysis of individual building renovation roadmaps as an instrument to achieve national energy performance targets”. https://ibpc2018.org/proceedings/

eceee 2019 Summer Study on energy efficiency (ECEEE 2018). I.Maia, L. Kranzl. “Building renovation passports: an instrument to bridge the gap between building stock decarbonisation targets and real renovation processes”. https://www.eceee.org/library/conference_proceedings/eceee_Summer_Studies/2019/7-make-buildings-policies-great-again/building-renovation-passports-an-instrument-to-bridge-the-gap-between-building-stock-decarbonisation-targets-and-real-renovation-processes/

Sustainable Built Environment D-A-C-H Conference (SBE 2019) I.Maia, L. Kranzl. “Defining a framework to apply retrofitting optimisation models for long-term and step-by-step renovation approaches”. https://iopscience.iop.org/article/10.1088/1755-1315/323/1/012175/pdf

17th Conference of International Building Performance Simulation Association (IBPSA 2021). I.Maia, L. Kranzl.“ Analysis of step-by-step individual roadmaps – what can we learn about the practice?” https://doi.org/10.26868/25222708.2021.30347

III. Conference presentations:

International Association for Energy Economics (IAEE):

- 2019: Long-term and step-by-step deep renovation approach including building owner’s ability to invest in a retrofitting optimisation model https://iaee2019ljubljana.oyco.eu/
- 2022: Data-driven estimation of building owners’ budget restrictions on investing in deep renovation https://iaee2022.org/

7th European User Conference for EU-Microdata (virtual), 2021. I.Maia, L. Kranzl. F. Schipfer, M.Lang. „EU SILC Database analysis: identifying techno-socio-economic building archetypes and their available budget to invest on building energy performance improvement. A cross country comparison.” https://www.gesis.org/fileadmin/upload/dienstleistung/daten/amtl_mikrodaten/europ_microdata/Presentations_2021/Maia_Kranzl_M%C3%BCller_Schipfer_Lang_7th_EU_UC.pdf

Report:
L. Kranzl. A. Müller. I. Maia. R.Büchele. M. Hartner., 2018, „Wärmezukunft 2050. Erfordernisse und Konsequenzen der Dekarbonisierung von Raumwärme und Warmwasserbereitstellung in Österreich – Endbericht“. https://www.igwindkraft.at/mmedia/download/2018.02.05/1517825327514183.pdf

14 Appendix II: iBRoad Roadmaps techno-economic assessment

The analyses performed aimed to provide insights about how the staged renovation approach is understood and interpreted in the praxis by the energy auditor. And, verify if calculated energy performance in the energy auditing practice are in line with national long-term renovation strategies, consequently, with the EU's building decarbonisation strategy. The present methodology consisted of mainly two parts. In the first part, the results from energy performance calculation provided in the iBRoad roadmaps were e statistically described in terms of the number of buildings per country, building construction period, total investment costs, and the number of steps specified in the roadmap. In the second part, the roadmaps were assessed according to defined LTRS indicators. In this part, firstly, of a literature review of the existing national long-term renovation strategies. Secondly, based on this literature, indicators will be defined and the roadmaps are assessed according to them. Recently, a study assessing the until now delivered LTRS across the EU Member States stated that many LTRS' are still uncompleted or do not fill all the requirements (Staniaszek et al., 2020). Spain and Flanders Region (Belgium) were cited as best-practice examples. Ideally, the iBRoad roadmaps and their accordance with LTRS should be assessed according to the country-specific LTRS, respectively, Bulgaria, Poland, and Portugal. However, Bulgaria and Poland have not submitted their LTRS yet and the Portuguese LTRS was considered incomplete for the present study. Because of that, the documents provided from Spain (Ministerio de Fomento, 2017) and Flemish Region (Belgium) (Flemish Region, 2017) served as a guideline to define and propose indicators to assess the LTRS. Finally, the consistency will the LTRS indicators are also expressed in form of a final scoring – equally-weighted average.

According to the National Long-term renovation strategy of the Flemish Region, energy performance regulations from 2015 have established that "major energy renovation of homes, apartments, offices, and schools were required to comply with a global energy performance requirement (E90)". Furthermore, major energy renovation has been defined according to the following criteria:

- At least 75% of the building elements adjacent to the outside air have to be insulated;
- Installation of a ventilation system;
- Replacement of the heating system
- 45% primary energy savings (achievement of level E90)

Under the requirements, for cost-effective approaches (see also the chapter above Long-term renovation strategy), the document suggests the economic indicator (TCC) evaluate economically the renovation measures over a period of 30 years. This indicator expresses the building's life-cycle costs and includes initial investment costs, energy consumption costs, annual maintenance costs, replacement costs, the residual value of investments, subsidies, and CO2 emissions costs.

While the Flemish LTRS focus on the technical characteristics of deep renovation activities, the Spanish LTRS has a stronger focus on policy and financing instruments and regulations to facilitate and promote the deep renovation practices. Between other singularities, the Spanish document specifies the indicator of carbon dioxide emission ($kgCO_2/m^2$ year) to be used to rate the building's renovation targets.

Based on the previous literature, the following seven numeric indicators and criteria will be used to assess the roadmaps:

1. **Primary energy savings**

The indicator "primary energy savings" expresses the savings that should be achieved after all steps have been performed based on the initial building status quo:

$$\text{PEsav} = \frac{\text{PEinitial} - \text{PEstepX}}{\text{PEinitial}}$$

Equation 20

PEsav = primary energy savings [%]

PEinitial = primary energy initial (without renovation) [kWh]

Step X = last renovation step, according to the roadmap

PEstepX = primary energy in the last renovation step [kWh]

2. **Carbon dioxide emission savings**

The indicator "carbon dioxide emissions savings" expresses the savings that should be achieved from the initial building status quo and after all steps have been performed.

$$\text{CO2sav} = \frac{\text{CO2initial} - \text{CO2stepX}}{\text{CO2initial}}$$

Equation 21

CO2sav = carbon emission savings [%]

CO2initial = carbon emission initial (without renovation) [$kgCO_2$]

Step X = last renovation step, according to the roadmap

CO2stepX = carbon emission in the last renovation step [$kgCO_2$]

3. **Heating system replacement**

The measure heating system replacement has to be foreseen in the roadmap, to guarantee that a more efficient heating system is installed.

4. **Renewable energy source for heating**

Beyond the energy efficiency of the heating system, also its energy source (if renewable or not) is relevant to be in line with decarbonisation targets. Therefore, preferably renewable energy sources should be installed.

5. Available incentives

As affordability is one of the main barriers to perform deep renovation, the EU member states should design attractive financing schemes.

6. Payback time

The total period to return the initial investments called payback time. Although no legislation regulates that the payback time should be used as indicator, this is considered by building owners (or not buildings experts) to be a easily understandable indicator. The minimum payback time assumption should be reasonable and acceptable value, especially from the building owner's perspective.

$$\mathrm{PBT} = \frac{\mathrm{IC}-\mathrm{L}}{(\mathrm{EC}+\mathrm{OMC})\mathrm{savings}}$$

Equation 22

PBT = pay back time [a]

IC = initial investment for renovation activity [Euro]

L = available incentive [Euro]

EC savings = energy costs savings due to the heating system replacement [Euro]

OMC savings = operation and maintenance costs due to the heating system replacement [Euro]

7. Investment net present value

The investment net present value allows an economic evaluation of renovation related investment as well as building-related expenditures (energy and maintenance costs) and available incentives. It calculates the net present value of the investment for a period of 30 years.

$$\mathrm{IPV} = \frac{\mathrm{IC}-\mathrm{EC}-\mathrm{OMC}-\mathrm{L}}{(1+\mathrm{r})^{\mathrm{t}}} + \frac{\mathrm{R}}{(1+\mathrm{r})^{\mathrm{T}}}$$

Equation 23

IPV = investment net present value [Euro]

IC = initial investment for renovation activity [Euro]

EC = energy costs [Euro]

OMC = operation and maintenance costs [Euro]

L = available incentive [Euro]

r = return rate, 3% [%]

t = year [a]

T = assessment period, 30 years [a]

Compliance with LTRS indicators

In this analysis, the 50 roadmaps were assessed according to the seven indicators in the chapter *Method*. The criteria used are:

1. Primary energy (PE) savings[4] >45%
2. Carbon dioxide emission[4] (CO_2) savings >70%
3. Heating system (HS)[4] replacement = yes
4. Installation of renewable energy source[4] (RES) = yes
5. Available incentives = yes
6. Payback time (PBT) < 7 years
7. Investment net present value (IPV) > 0

As the roadmaps did not specify the time when each step is performed and also no recommendation for calculation in case of a step-by-step roadmap, the present paper assumed in the calculations that all steps are performed at the same time. Further aspects related to that will be discussed in the chapter *Conclusion*.

Table 23: Percentage of compliance per country, indicators primary energy demand savings and carbon dioxide emission savings

	Percentage of compliance	
Country	PE sav > 45%	CO_2 sav > 70%
PT	89%	78%
PL	65%	18%
BG	87%	47%

In all countries, the primary energy savings requirements were achieved. However, the carbon dioxide requirements were not achieved a high percentage of buildings in Poland, followed by Bulgaria. The main difference relies on the energy source of the heating system: while in Portugal biomass is used, in Poland hard coal and natural gas are still very common. In Bulgaria, the not complaint roadmaps present as a second energy source (probably for domestic hot water supply) natural gas, hard coal, or electricity. And, although the main energy source was wood or electricity (foreseen on the roadmap), the percentage of second energy source supply is still high and affected higher CO_2 emission savings.

Table 24: Percentage of compliance per country, indicators heating system replacement and renewable energy source

	Percentage of compliance

[4] Building's main energy source

Country	HS replacement	RES replacement
PT	89%	89%
PL	76%	29%
BG	93%	87%

In all countries, the heating system replacement requirements were achieved. But, the replacement for renewable energy sources was not achieved in Poland. In Portugal, the most roadmaps advise heating system replacement to a biomass boiler, while in Bulgaria to a heat pump and in Poland to a condensing gas boiler.

Table 25: Percentage of compliance per country, indicator available incentive and investment net present value

	Percentage of compliance	
Country	HS replacement	RES replacement
PT	89%	89%
PL	76%	29%
BG	93%	87%

Ideally, the net present value should be positive; otherwise, it is not economically feasible. Especially in deep renovations, energy consumption costs savings, and sufficient incentives are benefits to improve the net present value and turn it positive. However, the results show in all countries, that the availability of incentives is quite low. And, no roadmap with a positive investment net present value.

Table 26: Percentage of compliance per country, indicator payback time

	Percentage of compliance
Country	PBT < 7a
PT	44%
PL	6%
BG	20%

In all countries, less than half of roadmaps achieve the requirements regarding the indicator payback time. The low percentage in Poland reflects the fact that the calculated energy consumption savings were also very low. In terms of final scoring, no roadmap full filled all seven indicators. But, 4 buildings in Portugal and 1 in Bulgaria full-filled more than 80% of the requirements.

Conclusion

Until now, not all EU-member states have submitted their LTRS or have submitted uncompleted documents. From the iBRoad pilot countries, Bulgaria and Poland have not submitted their LTRS yet and the Portuguese LTRS was considered incomplete for the present study. A recent study (Staniaszek et al., 2020) cited Spain and Flanders Region (Belgium) as LTRS best-practice examples, both of these documents were deeply analysed and guided the definition of seven indicators and their criteria.

The results showed that in terms of final scoring, no roadmap full filled all seven indicators. But, 4 buildings in Portugal and 1 in Bulgaria full-filled more than 80% of the requirements. The analysis also shows different tendencies in terms of heating systems and respective energy sources. In Portugal, the biomass boiler was the most recommended heating system. In Poland, the building stock decarbonisation targets still represent a big challenge as fossil fuel sources have been frequently recommended in the roadmaps. And in Bulgaria, although many roadmaps suggested the replacement by heat pumps, the structure of gross electricity generation in this country consists mainly of 39.2% (hard coal), 37.4% (nuclear energy), 15.8% renewable (IAEA, 2020).

The percentage of compliance with the economic indicators (availability of incentives, investment net present value, and payback time) were very low, in all countries. This makes evident the economic barriers faced by building owners in real life. There is still a need to increase even more the available incentives for deep renovations, with incentive sums and financing schemes that turn economically feasible the investments on a deep renovation. Also, mechanisms as CO2 taxes are important to accelerate the replacement by renewable energy sources. These economic barriers still have to be overcome by EU-member states to accelerate their national building stock decarbonisation. In Spain, according to Spanish LTRS, many regulative efforts will be done the direction of increasing incentives.

The presented results were based on the information available in the roadmaps (or iBRoad-Plans) developed by the energy auditors. And, the consistency and correctness of the roadmaps themselves were not part of the present scope. In the context of the iBRoad project, additional building-related information would be available in the logbook (or iBRoad-Log) for the same building. However, when treated as a single document, further building-related information could be added to the roadmap: building energy needs, building-related information (U-values), historic building envelope activities, and exact specification of the proposed measure (for example the thickness and the characteristic of the insulation material).

The last point to be discussed refers to the step-by-step approach. The number of steps is an important parameter as it allows a qualitative indication about the time to complete the whole building renovation. If divided into many steps, there is a higher risk that the building owner interrupts the renovation process before finishing the whole building renovation. And, this is one of the most critical points related to the step-by-step approach and its implementation. Because of that, the Salzburg Land (in Austria) has for example limiting the number of steps to a maximum of 3. The roadmaps analysed in this paper showed presented between 1 and 5 steps. There could not be identified any correlation between the number of steps and other parameters as construction year, primary energy demand, or total investment step. This indicates that the choice of the number of steps might have been done individually, as expected in the project.

Referring to the time, when each step should be performed, the roadmap did not specify it, being up to the building owners to decide when to perform each step. Further tools could be developed to support energy auditors on specifying the time when each step should be performed – as the step-by-step optimisation model developed by the authors, which calculates the optimum timing of each step (Maia and Kranzl, 2019).

Although the EPBD (2018/844/EU) introduces the step-by-step approach, it does not introduces specific metrics to evaluate the energy and carbon emission savings of step-by-step roadmaps. However, there is a need to use metrics that takes into account the time aspect of the roadmaps, otherwise deep renovation might not happen as fast as necessary to achieve EU's building stocks decarbonisation targets. Exemplary metrics could be cumulated energy savings, minimum energy savings per step and estimated cost per saved primary energy (or energy needs). Finally, new financing schemes that take the singularities of the step-by-step approach into account should be designed.

15 Appendix III: Staged optimisation model input data

The model was run with following input data:

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 / 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

16 Appendix IV: National Long-Term Renovation Strategies

The revised Energy Performance Building Directive EPBD (2018/844/EU) calls all EU countries in Paragraph 2a to establish their national long-term renovation strategy (LTRS) and submit their first LTRS to the European Commission until 10 March 2020. However, not all Member States have done it so far or have presented incomplete documents. The LTRS should enable building stock's energy transition and decarbonization by 2050, and they will be part of EU countries' integrated national energy and climate plans (NECPs) (European Commission, 2019). Article 2a of the EPBD suggests a structure for the LTRS and presents all requirements that the Member States should specify. These are (European Parliament, 2018):

1a - Overview of the national building stock and expected share of renovated buildings in 2020;

1b – Cost-effective approaches to renovation considering potential relevant trigger points;

1c – Policies and actions to stimulate cost-effective deep renovation, including, for example, introducing an optional scheme for building renovation passports;

1d – Overview of policies and actions to target worst performing segments of the building stock, split-incentive dilemmas and market failures and an outline of actions that contribute to the alleviation of energy poverty;

1e – Policies and actions to target all public buildings

1f – Overview of national initiatives to promote smart technologies and well-connected buildings and communities, as well as skills and education in the construction and energy efficiency sectors;

1g – Evidence-based estimation of expected energy savings and wider benefits, such as those related to health, safety, and air quality;

2 – Roadmap with measures and progress indicators, with a view to the long-term 2050 goal of reducing EU GHG emissions by 80-95% compared to 1990. The roadmap shall include indicative milestones for 2030, 2040, and 2050;

3 – To support mobilization of investments, facilitate access to appropriate mechanisms for:

a. Aggregation of projects and packaged solutions

b. Reduction of perceived risk for investors and private sector

c. Use of public funding to leverage additional private-sector investment or address specific market failures

d. Guiding investments into an energy-efficient public building stock

e. Accessible and transparent advisory tools

4 - Include summary results of the public consultation into the LTRS and establish modalities for consultation in an inclusive way during its implementation

5 – Include implementation details of the latest LTRS